A HIGH BIT RATE FLEXIBLE MAC PROTOCOL FOR MONITORING APPLICATIONS USING 60GHZ RADIO TECHNOLOGY

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A HIGH BIT RATE FLEXIBLE MAC PROTOCOL FOR MONITORING APPLICATIONS USING 60GHZ TECHNOLOGY

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To my Parents and Giants on whose shoulders I stood

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LIST OF SYMBOLS AND ABBREVIATIONS

ACK	Acknowledge
ADC	Analog to Digital Converter
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BER	Bit error rate
BFN	Beam Forming Network
BPSK	Binary Phase Shift Keying
BS	Base station
BSS	Basic Service Set
BW	Bandwidth
CCD	Charge Coupled Device
CO	Central Office
CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
DAC	Digital to Analog converter
dB	Decibel
dBm	Measured power referenced to one milliwatt
DLC	Data Link Control
DPSK	Differential Phase Shift Keying
EIRP	Equivalent Isotropic Radiated Power
EOD	End of Data
EOT	End of Transmission
f_c	Center Frequency

FCC	Federal Communication Commission
FDMA	Frequency division multiple Access
FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum
F_{RE}	Range Extension Factor
FTTH/P	Fiber to the home/premise
Gbps	Giga bit per second
GHz	Gigahertz
G_r	Receive Antenna Gain
G_t	Transmit Antenna Gain
H	Hessian matrix
h_r	Receive Antenna Height
h_t	Transmit Antenna Height
HDTV	High-definition television
IBSS	Institute of Electrical and Electronic Engineers
IEEE	Independent Basic Service Set
ISM	Industrial, Scientific & Medical
kbps	kilobit per second
km	kilometers
LEACH	Low Energy Adaptive Clustering Hierarchy
L_{FSL}	Free Space Path Loss
L_{FSL-dB}	Free Space Path Loss in decibel
LLC	Logic Link Control
LOS	Line Of Sight
MAC	Medium Access Control

Mbps	Megabit per second
MHz	Megahertz
MN	Monitoring node
msec	milli-second
µsec	micro-second
NLOS	Non Line of Sight
nsec	nano-second
OFDM	Orthogonal frequency division multiplexing
OSI	Open System Interconnection
PDA	Personal Digital Assistant
PHY	Physical layer
PON	Passive Optical Network
P_r	Power Received
P_t	Power Transmitted
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RECACK	Acknowledge Received
RF	Radio frequency
ROF	radio-over-fiber
RTS	Request to Send
Rx	Receive
SBA	Switched Beam Antenna
σ	Node Density per unit area
SMAC-S	Self organizing Medium Access Control for Sensor Networks

SMF	Single mode fiber
$t_{delay,nor}$	Average delay in Normal mode
$t_{delay,Ic}$	Average delay in Icarus mode
$t_{delay,resync}$	Average delay in Resync mode
TDM	Time division multiplexing
TDMA	Time Division Multiple Access
θ	Antenna Beamwidth
TRAMA	Traffic Adaptive Medium Access
Tx	Transmit
UWB	Ultra Wide Band
WDM	Wavelength division multiplexing
WiFi	Wireless Fidelity
WPAN	Wireless Personal Area Network
x_*	Final value of Newton's Method
x_n	nth iterate in Newton's Method

SUMMARY

In recent years there has been a growing trend in optical wireless convergence. One particular aspect of this is 60 GHz radio-over-fiber technology. It is intended for use in wireless personal area networks. However, we think that the same technology could be used for monitoring applications in the indoor environment. It could be used to detect emergency situations or to detect intruders. We shall examine reasons why this choice might be a suitable one. We shall then propose a MAC layer protocol to accomplish this task. Since in case of emergency we might require to obtain data from only one node for an extended duration, flexibility in implementation is required. We shall develop an adaptive MAC protocol where this would be possible. We accomplish this by including two protocol modes called the Icarus mode, which is to be used in case of an emergency and the Resync mode which is used when normality is restored. A significant problem at high frequencies is that the beam becomes increasingly narrow and behaves more in a ray like condition. This implies that particularly in an indoor environment it is possible that the beam may be accidentally blocked. In this case the node must be able shift the beam in order to enable communication. We demonstrate three such strategies and offer a comparative analysis.

CHAPTER 1

PROBLEM SETTING

Introduction

In this thesis we are attempting to develop a Medium Access Control (MAC) protocol that would address the issues dealing with channel access policies using 60 GHz Radio over fiber technology. We hope that such an indoor network would be used for monitoring critical areas when failure to monitor could result in significant damage or even death. During the course of this thesis we shall develop the ideas we believe are critical if such systems are to be deployed. Hence before proceeding further we shall first consider an example where such technology might be used.

Example: Highly secure locations which are susceptible to human attack.

A potential application for such a network is in locations such as airports, railway stations, banks and other important locations that are prone to human attack.

There has been, in recent times, an increase in the levels of terrorist activity. Terrorists have targeted vulnerable locations in particular railway stations in Mumbai, Madrid and London. They have bombed hotels in Bali and Karachi. For both prevention of these crimes and bringing the criminals to justice it is vital that the security services of any country have good visual information about these people. In fact, the London bombers were arrested on the basis of an image of the terrorists captured by a CCTV (Closed Circuit Television). This is as shown in Fig 1.1.

Fig 1.1: The bombers caught on CCTV at Luton railway station at 7:21 a.m. on 7 July. Courtesy: BBC News

In addition to the threats that terrorists pose to the safety and well being of citizens, one also has to take into account the steady rise in common crime such as bank robberies, armed robberies of stores etc. Most of these locations use low bit rate analog cameras for surveillance. This results in very low resolution images from which it is barely possible to make out the contours of a person's face as can be seen in Fig 1.2. This makes it nearly impossible to apprehend the miscreant.

In these cases it is clear that High-Def cameras would be of the greatest possible assistance to the law-enforcement agencies. However, this then raises the issue of transmitting this information in real time to the police for swift action.

Currently most high-definition footage is stored on hard disk. These can be retrieved by the police only after the alarm has been raised and the criminal has escaped.

Fig 1.2: Low quality analog images of a bank. Note the impossibility of determining the facial features of the person

If in addition to the existing methods we could provide high definition images to desired authorities and in the case of an emergency simultaneously provide high definition images of the same to the emergency services. By this method then valuable time can be saved and the mechanism would become more robust. It would also be helpful if the emergency services knew of the exact location of the leak. Robust and deterministic determination of emergency is more important than cost or other concerns. In general, there are several rooms that have to be monitored. Thus any scheme designed would have to enable frequency reuse. Thus briefly summarizing the desired system must have the following capabilities:

1. Must be able to transmit high definition images uncompressed
2. Frequency reuse should be possible
3. Must be possible to transmit information to emergency services who may be a couple of miles away
4. Cost is not a major concern.
5. The monitoring units are more likely to be embedded, in nature. Thus the network shall be closer to an infrastructure network rather than an ad-hoc network.

(We use the term “monitoring node” as the term “sensor” is used to emphasize the low power requirement. Energy efficiency is a principal concern. Sensor nodes are usually meant for acquisition of data usually based on events. In most cases, the sensor is idle for most of the time. On the contrary our monitoring nodes shall be active for most of the duration.)

Thus we need to find a medium of transmission that can meet all of the above requirements in both of the above cases. We now propose that 60GHz based Radio over fiber technology might be a good option for this sort of application.

Why 60 GHz based RoF networking might be a good option

As has been discussed extensively in the literature, the major benefit of millimeter waves based communication is the extensively large available bandwidth. Also it must be noted that the spectrum between 57 and 64 GHz (U.S.A.) and 59 to 66 GHz (Japan) are unlicensed as shown in Fig 1.3. The large bandwidth makes it possible to transmit images and videos in high definition format uncompressed. This opens up the possibility for designing a wireless multimedia monitoring network. It must be noted that the images need not be only on the visible part of the spectrum. One could take high definition Infrared images as well. This makes it possible to obtain direct visual input on a wide range of phenomena. For instance we could obtain a high definition thermal profile of a moving individual.

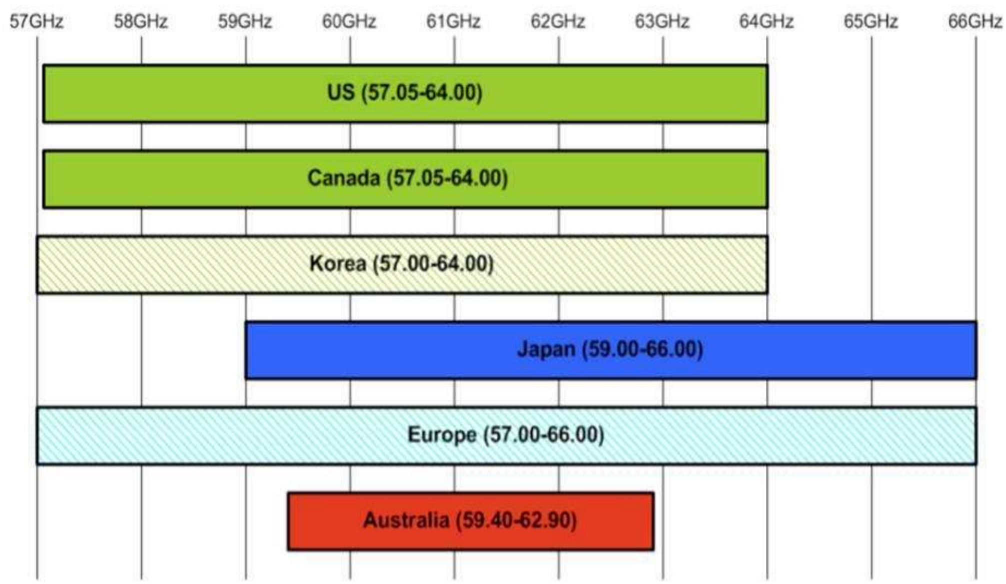

Fig. 1.3: Spectrum allocation at the ISM band in different countries. Note the large bandwidth availability.

However, there exists a major drawback of communication systems operating at 60 GHz is that communication over a range of a few meters may not be possible. One method of increasing the range is to use a Radio-over-Fiber system. A major benefit is the large available bandwidth at optical frequencies. At a single optical frequency it is possible to transmit multiple wireless frequencies. Also this method makes it possible to utilize the large quantities of pre-existing backbone fibers that already exist for long distance communication. Thus one could potentially receive high definition multimedia sensor data several miles away from the site of measurement. The author is not aware of any other scheme that offers the same range of transmission of high definition images. But fiber based technology is a wired mode transmission. This implies that at the global level the network is static. However, it is possible for us to move sensors around the room over the range of a few meters. Thus we obtain a "globally static locally dynamic" monitoring network. Even in the case of fixed embedded monitoring network it may not be possible to connect all the sensors directly to the fiber as the position of the sensor may not be very convenient with respect to the pre-laid fiber. For instance, it might be necessary to monitor every nook and corner of the room, in order to prevent any serious mishap. However to connect each and every node directly to fiber is clearly not possible. The use of fiber gives us another additional advantage besides considerably extending the range of transmission of the multimedia data. The large available bandwidth of optical frequencies implies that for sensing critical phenomena, it is possible to introduce redundancy thereby making the sensing process more robust. Consider the case that we have made the object of our study. The large available optical bandwidth implies that we can place multiple image sensors to sense even the tiniest detail etc. This makes it possible to sense critical phenomena in a deterministic way in case one of the nodes fails. This is of critical importance as most common sensor networking methodologies employ statistical methods of prediction in case one of the sensors fails. This method can only be effective within a certain confidence interval. Thus there exists a possibility no matter how remote that an error may occur. This is unacceptable in our case

Summary

In summary, we have seen some important cases where high definition video and images could significantly improve the quality of monitoring. In order to network these monitoring nodes, we have suggested the use of 60 GHz Radio-over-Fiber (RoF) networking technology. In order to proceed further, we shall now study some of the important aspects of this technology.

CHAPTER 2

BACKGROUND

Introduction

We introduced in the previous chapter, 60 GHz Radio-over-Fiber technology. We briefly indicated why this technology might be suited for high bit rate monitoring networks. The 60 GHz band is a type of broadband access technology. Before we proceed further, we shall introduce some similar technologies and study their respective advantages and disadvantages.

The development of Broadband Access technologies was driven primarily by high-speed broadband penetration and ongoing growth of the Internet traffic among residential and business customers. These have been placing a huge bandwidth demand on the underlying telecommunications infrastructure.

Wired Technologies

These technologies can be either wired or wireless the principal wired technology is PON technology. PON stands for “Passive Optical Network” which means that there are no active elements between the Central Office and the customer [2]. A PON is a point-to-multipoint network architecture in which optical splitters are used to enable a single optical fiber to serve multiple premises. They are classified into two primary categories TDM-PON (Time Domain Multiplexing-PON) and WDM-PON (Wavelength Domain Multiplexing-PON) depending on whether the users are allocated individual time slots or individual wavelength for transmission.

Currently, the FTTH/P (Fiber to the Home/Premise) networks using passive optical network (PON) are highly recognized as the most promising candidates for next generation access systems.

Now we must understand why all optical or completely wired networks would not be suitable for our application. It is certainly true that fiber could easily accommodate the bandwidth requirements of our applications. Cat 5 (Category 5) and Cat 7 (Category 7) cables which are high bandwidth twisted pair Ethernet cables could also be used. But there are other restrictions beside bandwidth that make it exceedingly difficult to apply these in practice. In a fiber/wired network, fiber/cable must reach each and every node if communication is to take place. This introduces the following difficulties. Firstly additional costs have to be incurred. Fiber must reach each and every node which implies expensive optical equipment for every node must be provided. This shall significantly raise the costs. Also the data rate generated by a single high definition monitoring node shall result in resources not being optimally utilized. In the case of cables, the significant problem is that the distance between the central controller and the node (no base station is needed in this case) can be at most 100 m which is highly restrictive in our case. As has been explained the emergency or security services may be situated a mile or even further away. Secondly, position of nodes is fixed at the time of installation and cannot be altered. This makes it very difficult if the network has to be reconfigured at a later date. Then the apparatus will have to be dismantled and reinstalled for the node which increases costs at a later date. It might be necessary to monitor every nook and corner of the room, in order to prevent any serious mishap. However to connect each and every node directly to fiber is clearly not possible. Also, scalability is poor i.e. we cannot add nodes at a later date. This would require adding additional fiber from the central controller all the way up to the individual node, reconfiguring the entire network so as to create a time slot or a wavelength for the node to transmit.

Hence it is much easier to use a hierarchical architecture as suggested where the central controller is connected using fiber to several base stations and they in turn are connected wirelessly to the nodes. Thus we reduce installations costs significantly. Also if we wish to adjust node position or add more nodes at a later date, it would be possible to do this rather easily as all adjustments need only to be done locally.

Wireless Technologies

The aforementioned PON networks are an example of wired broadband access technology. Another significant development in recent years has been the development of broadband wireless access networks. In recent years, wireless networks are becoming more pervasive. This tremendous growth is mainly accelerated by advanced wireless communication technologies, inexpensive wireless equipment, and broader access availability. These networks are transforming the way people use computers and other personal electronic devices at work, home, and when traveling. There are many wireless communication technologies that can be differentiated by frequency, bandwidth, range, and applications.

In particular, we are concerned with a specific type of network called WPAN. WPAN stands for “Wireless Personal Area Network” and it stands for wireless networks that have a maximal signal range of 10 meters, and these networks are used for the connection of consumer electronic devices with each other such as personal digital assistants (PDAs) or mobile phones. Some of the commonly used WPANs are defined below

Name	Origin	Frequency band	Bit rate	Signal range
Bluetooth	2004	2.4 GHz	2.1 Mb/s	10 m
UWB	2007	3.1-10.6 GHz	500 Mb/s	10 m
ZigBee	2004	2.4 GHz	250 kb/s	10 m
WiFi	2004	2.4GHz/5GHz	11 Mb/s or 54Mb/s	100ft

Table 2.1: Comparison of various currently used WPAN technologies

Bluetooth

Bluetooth is designed for exchanging data over short distances from fixed and mobile devices, creating personal area networks (PANs). It can connect several devices, overcoming problems of synchronization

Bluetooth uses a spread spectrum technique in the 2.4 GHz band, which ranges from 2.4 to 2.4835 GHz, for a total bandwidth of 83.5 MHz. Bluetooth uses frequency hopping spread spectrum (FHSS) with 1 MHz wide channels. Frequency hopping is less sensitive to strong narrow band interference that only affects a few channels. It uses ARQ (Automatic Repeat Request) at the MAC level, i.e., it retransmits the packets for which no acknowledgement is received. It uses both time and frequency diversity. [4]

When the base is first turned on, it sends radio signals asking for a response from any units with an address in a particular range. Since the handset has an address in the range, it responds, and a tiny network is formed. This is called a Piconet. The aggregate throughput of a Piconet is independent of the traffic offered, because the access is centrally arbitrated. Efficiency is constant in a Piconet. It has to define power limitations for the devices, according to the limits imposed by the various telecommunications regulatory bodies. [4]

The maximum number of devices belonging to the network' s building block, i.e. the Piconet for Bluetooth 8 (7 slaves plus one master) for a Piconet. Up to 255 Bluetooth slaves can be put in park mode, a state where they do not participate in data exchanges while keeping synchronization with the master's transmissions. [4]

Bluetooth, in a nominal range of 10 m, allows the allocation of 20 different Piconets, each with a maximum aggregate data transfer speed around 400 kb/s. [4]

ZigBee [5,6]

ZigBee is a set of communication protocols using small, low-power digital radios based on the IEEE 802.15.4-2003 standard for wireless personal area networks (WPANs), such as wireless headphones connecting with cell phones via short-range radio. The principal advantages include simplicity and cost effectiveness compared with other WPANs, such as Bluetooth. It is particularly suited for applications that require a low data rate, long battery life, and secure networking.

Typical application areas include

- Home Entertainment and Control — Smart lighting, advanced temperature control, safety and security, movies and music

- Home Awareness — Water sensors, power sensors, energy monitoring, smoke and fire detectors, smart appliances and access sensors

- Mobile Services —payment, monitoring and control, security and access control, healthcare and teleassist

- Commercial Building — Energy monitoring, lighting, access control

- Industrial Plant — Process control, asset management, environmental management, energy management, industrial device control

ZigBee operates in the industrial, scientific and medical (ISM) radio bands; 868 MHz in Europe, 915 MHz in the USA and Australia, and 2.4 GHz in most jurisdictions worldwide. The technology is intended to be simpler and less expensive than other WPANs such as Bluetooth.

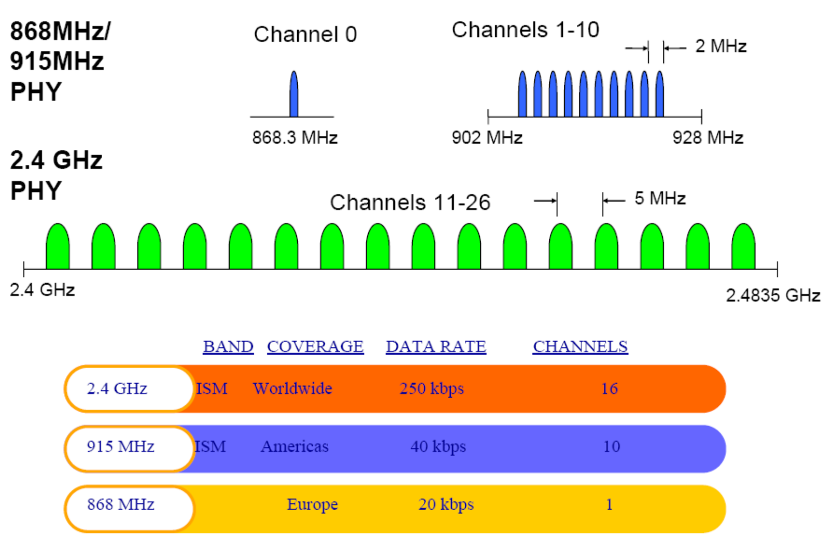

Fig.2.1: ZigBee Channels and Bandwidth. Courtesy: ZigBee Alliance [5]

ZigBee devices are required to conform to the IEEE 802.15.4-2003 Low-Rate Wireless Personal Area Network (WPAN) standard. The standard specifies the lower protocol layers—the physical layer (PHY), and the media access control (MAC) portion of the data link layer (DLL). As can be seen from Fig 2.1, this standard specifies operation in the unlicensed 2.4 GHz (worldwide), 915 MHz (Americas) and 868 MHz (Europe) ISM bands. In the 2.4 GHz band there are 16 ZigBee channels, with each channel requiring 5 MHz of bandwidth. The center frequency for each channel can be calculated, $f_c = (2405 + 5 * (ch - 11))$ MHz, where ch = 11, 12, ..., 26.

The radios use direct-sequence spread spectrum coding, which is managed by the digital stream into the modulator. BPSK (Binary Phase Shift Keying) is used in the 868 and 915 MHz bands, and orthogonal QPSK (Quadrature Phase Shift Keying) that transmits two bits per symbol is used in the 2.4 GHz band. The raw, over-the-air data rate is 250 kbit/s per channel in the 2.4 GHz band, 40 kbit/s per channel in the 915 MHz band, and 20 kbit/s in the 868 MHz band.

Transmission range is between 10 and 75 meters (33 and 246 feet) and up to 1500 meters for ZigBee Pro, although it is heavily dependent on the particular environment. The maximum output power of the radios is generally 0 dBm (1 mW).

The basic channel access mode is “carrier sense, multiple access/collision avoidance”(CSMA/CA). There are three notable exceptions to the use of CSMA. Beacons are sent on a fixed timing schedule, and do not use CSMA. Message acknowledgments also do not use CSMA. Finally, devices in Beacon Oriented networks that have low latency real-time requirements may also use Guaranteed Time Slots (GTS), which by definition do not use CSMA.

UWB

Ultra-wideband (UWB) is a radio technology that can be used at very low energy levels for short-range high-bandwidth communications by using a large portion of the radio spectrum. [7]

Ultra-Wideband (UWB) may be used to refer to any radio technology having bandwidth exceeding the lesser of 500 MHz or 20% of the arithmetic center frequency, according to Federal Communications Commission (FCC) [31]. Regulatory settings of FCC are intended to provide an efficient use of scarce radio bandwidth while enabling both high data rate "personal area network" (PAN) wireless connectivity and longer-range, low data rate applications as well as radar and imaging systems.

UWB devices can also be used for wireless communications, particularly for short-range high-speed data transmissions suitable for broadband access networks. Bit rates up to 480 Mbps can be attained.

To ensure that UWB devices do not cause harmful interference, this order [31] establishes different technical standards and operating restrictions for three types of UWB devices based on their potential to cause interference. These three types of UWB devices are: 1)imaging systems including Ground Penetrating Radars (GPRs) and wall, through-wall, surveillance, and medical imaging devices, 2) vehicular radar systems, and 3) communications and measurement systems.

The frequencies are allocated according to application as can be seen below [31]

Imaging Systems:

Ground Penetrating radar: below 960 MHz or in the frequency band 3.1-10.6 GHz.

Wall Imaging systems: below 960 MHz or in the frequency band 3.1-10.6 GHz.

Through Wall Imaging Systems: below 960 MHz or in the frequency band 1.99 -10.6 GHz.

Surveillance Systems: in the frequency band 1.99 -10.6 GHz.

Medical Systems: in the frequency band 3.1-10.6 GHz.

Vehicular Radar Systems: Center frequency of the emission and the frequency at which the highest radiated emission occurs are greater than 24.075 GHz. The -10 dB bandwidth must be between 22 and 29 GHz.

Communication and Measurement Systems: the frequency band 3.1-10.6 GHz

The power limitations as represented by the Equivalent Isotropic Radiated Power (EIRP) are dependent upon the frequency of operation

Frequency in MHz	**EIRP in dBm**
960-1610	-65.3
1610-1990	-53.3
1990-3100	-51.3
3100-10600	-41.3
Above 10600	-51.3

Table 2.2: Frequency vs. EIRP for UWB

This ECMA (European Computer Manufacturer Association) Standard [7] specifies a MultiBand Orthogonal Frequency Division Modulation (MB- OFDM) scheme to transmit information. A total of 110 sub-carriers (100 data carriers and 10 guard carriers) are used per band to transmit the information. In addition, 12 pilot subcarriers allow for coherent detection. Frequency-domain spreading, time-domain spreading, and forward error correction (FEC) coding are used to vary the data rates. FEC is a system of error control for data transmission whereby the sender adds redundant data to its messages which can be used by the Receiver to detect and correct error w/o asking the sender to resend data. The FEC used is a convolutional code with coding rates of 1/3, 1/2, 5/8 and 3/4.

UWB has been a proposed technology for use in personal area networks and appeared in the IEEE 802.15.3a draft PAN standard. However, after several years of deadlock, the IEEE 802.15.3a task group was dissolved in 2006. Slow progress in UWB standards development, high cost of initial implementations and performance significantly lower than initially expected are some of the reasons for the limited success of UWB in consumer products, which caused several UWB vendors to cease operations during 2008 and 2009

WiFi

Wi-Fi which is used synonymously for IEEE 802.11 technology is actually a trademark of the Wi-Fi Alliance that may be used with certified products that belong to a class of wireless local area network (WLAN) devices based on the IEEE 802.11 standards.

It is important to note that as the range of WiFi is roughly 100 ft, it does not strictly speaking qualify as a WPAN system. However, given its wide usage in device inter-networking it might be useful to gain more insight into this protocol.

Both protocols use a spread spectrum technique in the 2.4 GHz band, which ranges from 2.4 to 2.4835 GHz, for a total bandwidth of 83.5 MHz. Wi-Fi can also use the 5 GHz band. Wi-Fi uses different techniques with about 16 MHz wide channels. Both standards use ARQ at the MAC level, i.e., they retransmit the packets for which no acknowledgement is received. [4]

The aggregate throughput on a BSS (Basic Service Set) is dependent on the traffic offered, due to the distributed CSMA/CA technique, which uses collisions as a means of regulating access to the shared medium. Efficiency in a BSS is lower at higher load [4]. The maximum number of devices belonging to the network' s building block, i.e., BSS for Wi-Fi, is 2007 for a structured BSS and unlimited for an IBSS (Independent BSS).

Wi-Fi allows interference-free allocation of 4 different BSSes, each with aggregate transmission speed of 910 kb/s in a nominal range of 100 m, or 31.4 Mb/s in a nominal range of 10 m. [4]

Wireless Channel Properties

We have in the previous sections studied in some detail the various currently used protocols for Wireless Personal Area Networks. We have also recommended that the 60GHz band would be the ideal medium for signal transmission for our problem setting. This particular band falls under what is also known as Extremely

High Frequency or EHF. As was evident from the previous sections, the properties of the protocol depend significantly on the wireless channel properties. Hence before proceeding further we shall examine the channel properties in this band.

Extremely high frequency is the highest radio frequency band. EHF runs the range of frequencies from 30 to 300 gigahertz, above which electromagnetic radiation is considered to be low (or far) infrared light, also referred to as terahertz radiation. This band has a wavelength of ten to one millimeter, giving it the name millimeter band or millimeter wave, abbreviated mmW.

Compared to lower bands, terrestrial radio signals in this band are extremely prone to atmospheric attenuation, making them of very little use over long distances. In particular, signals in the 57–64 GHz region are subject to a resonance of the oxygen molecule and are severely attenuated. While this absorption limits potential communications range, it also allows for smaller frequency reuse distances than lower frequencies. The small wavelength allows modest size antennas to have a small beam width, further increasing frequency reuse potential.

The 60 GHz band can be used for unlicensed short range (1.7 km) data links with data throughputs up to 2.5 Gbit/s. It is used commonly in flat terrain. The 60 GHz frequency, do not require a transmitting license in the US from the FCC, as it suffers from the effects of oxygen absorption as the 60 GHz does. [8]

Because of shorter wavelengths, the band permits the use of smaller antennas than would be required for similar circumstances in the lower bands, to achieve the same high directivity and high gain. The immediate consequence of this high directivity, coupled with the high free space loss at these frequencies, is the possibility of a more efficient use of the spectrum for point-to-multipoint applications. Since a greater number of highly directive antennas can be placed in a given area than less directive antennas, the net result is higher reuse of the spectrum, and higher density of users, as compared to lower frequencies. [8]

As explained above a significant factor in millimeter wave transmission is channel loss. We shall now study in detail its causes.

Free Space Path loss [8]

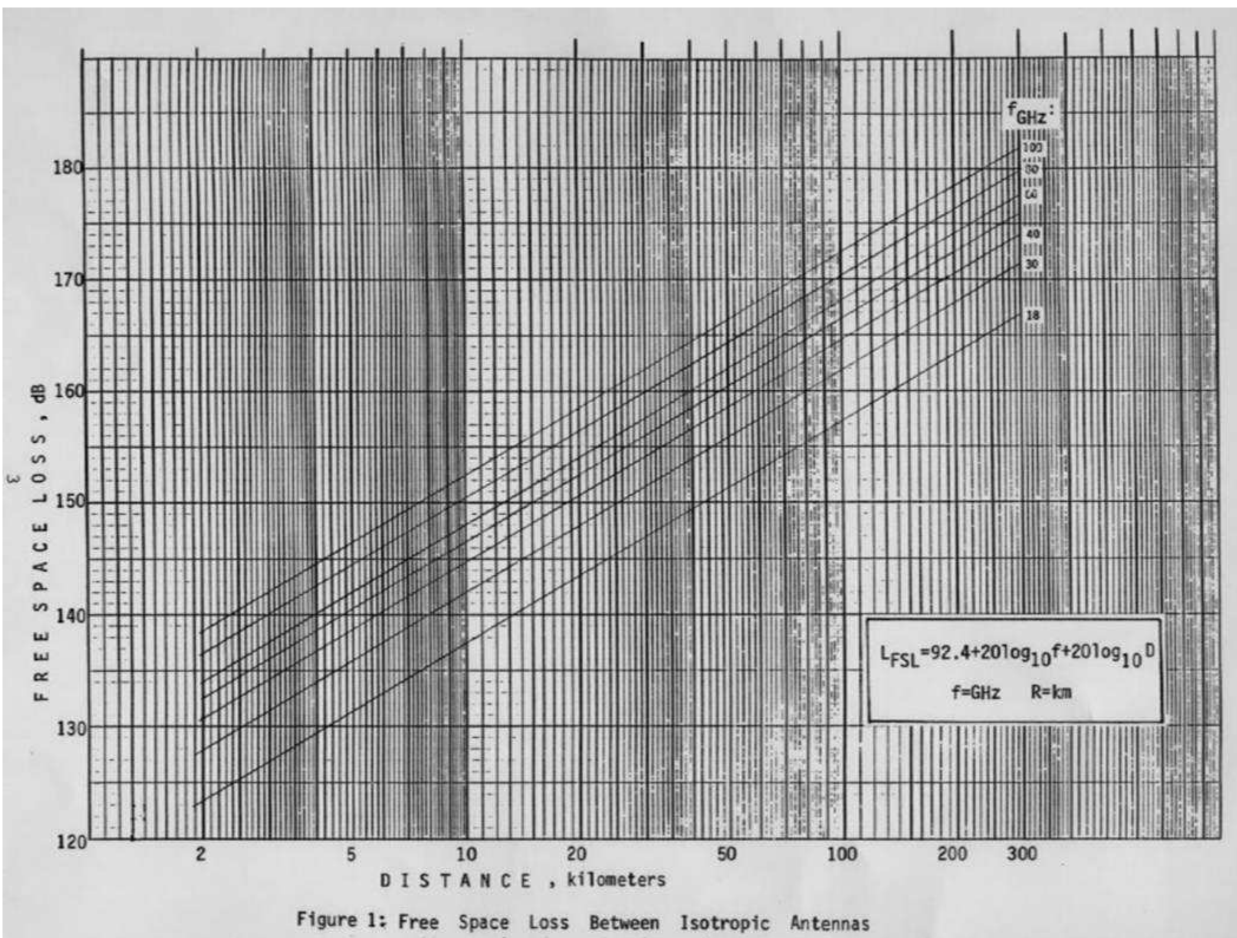

Fig. 2.2: Free space Path loss between Isotropic Antennas. Courtesy: FCC Bulletin on Millimeter Wave Propagation [8]

The frequency and distance dependence of the loss between two isotropic antennas is expressed in absolute numbers by the following equation:

$$L_{FSL} = (4\pi R/\lambda)^2 \text{ Free Space Loss}$$

where R: distance between transmit and receive antennas; l: operating wavelength. After converting to units of frequency and putting in dB form, the equation becomes:

$$L_{FSL\ dB} = 92.4 + 20 \log f + 20 \log R$$

where f: frequency in GHz; R: Line-of-Sight range between antennas in km. The results are plotted in Fig 2.2

Atmospheric Gases

Transmission losses occur when millimeter waves traveling through the atmosphere are absorbed by molecules of oxygen, water vapor and other gaseous atmospheric constituents. These losses are greater at certain frequencies, coinciding with the mechanical resonant frequencies of the gas molecules. Fig 2.3 gives qualitative data on gaseous losses. It shows several peaks that occur due to absorption of the radio signal by water vapor (H_2O) and oxygen (O_2). [8] At these frequencies, absorption results in high attenuation of the radio signal and, therefore, short propagation distance. For current technology the important absorption peaks occur at 60 GHz as shown in Fig 2.4.

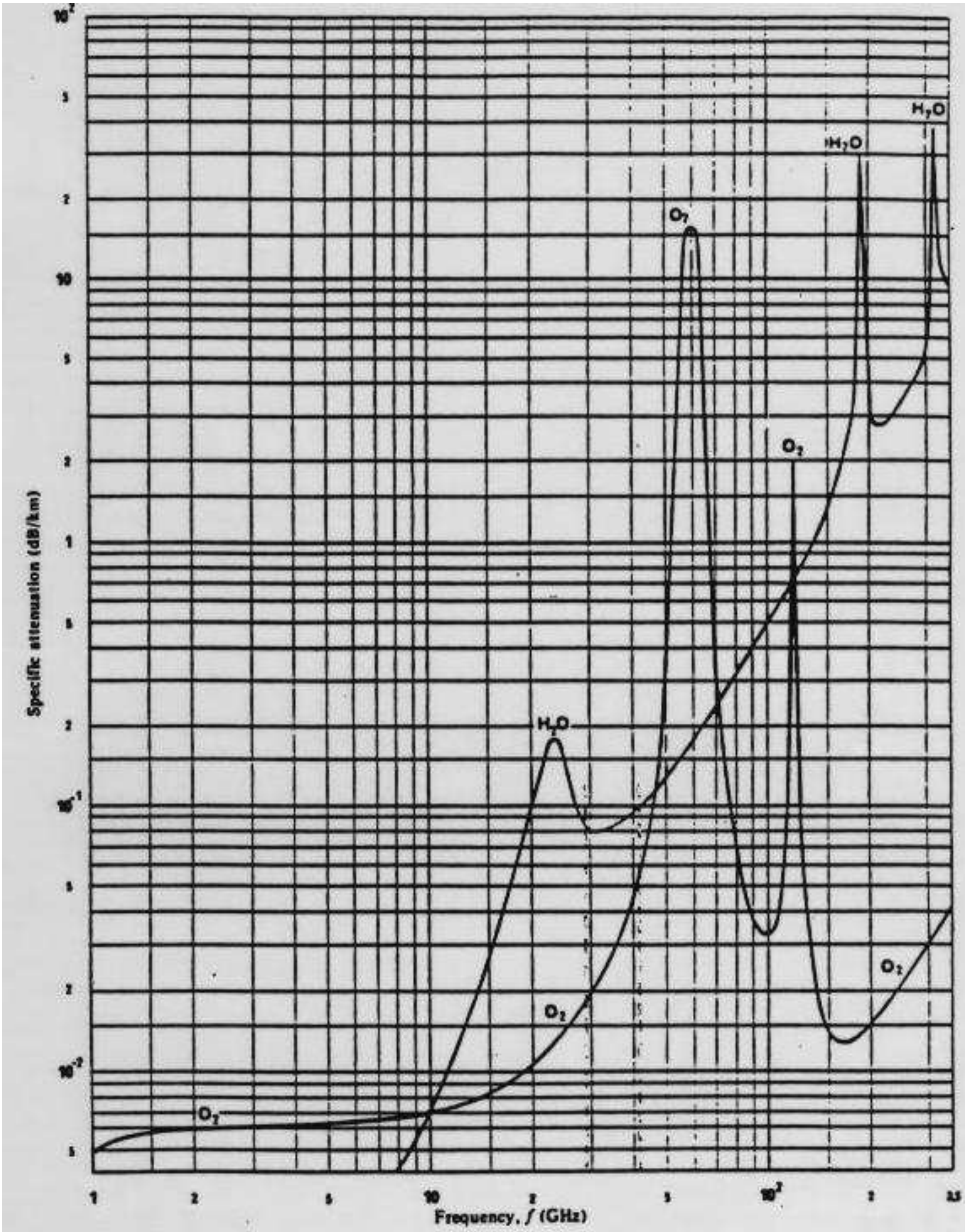

Fig. 2.3: Specific Absorption due to Atmospheric Gases. Courtesy: FCC Bulletin on Millimeter Wave Propagation [8]

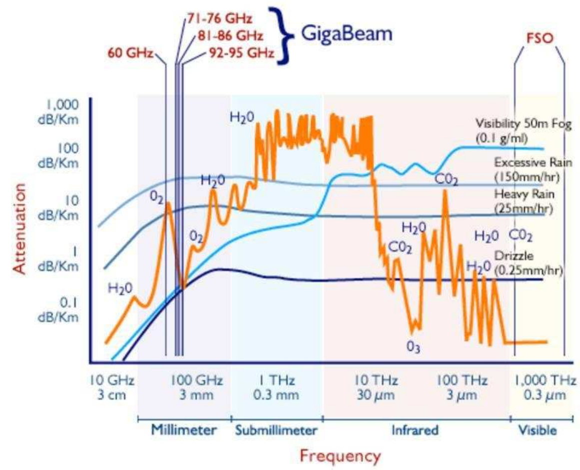

Fig. 2.4: Total Loss as a function of Frequency

Wireless Channels

Given below in Fig 2.5 is the division of the 57-64 GHz band into sub channels. As can be seen, This is more than sufficient in order to ensure high definition video and image communication which typically requires 1.5 Gbps

Channel Number	Low Freq. (GHz)	Center Freq. (GHz)	High Freq. (GHz)	Nyquist BW (MHz)	Roll-Off Factor
1	57.200	58.240	59.280	1664	0.25
2	59.280	60.320	61.360	1664	0.25
3	61.360	62.400	63.440	1664	0.25
4	63.440	64.480	65.520	1664	0.25

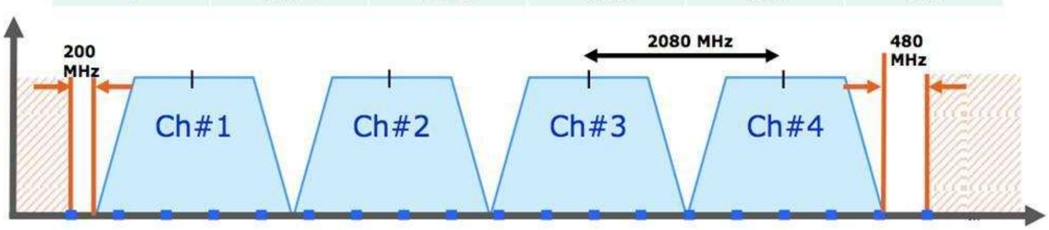

Fig. 2.5: Channels in the 57-64 GHz band. Note that the sub-channels roll-off gently. This is to ensure that the electronic devices are able to cope

Radio-over-Fiber Technology [2]

Today's wired networks based on fiber technologies have the capability of providing huge bandwidth to end users using optical fiber, but they are not flexible enough to allow convenient roaming connections. On the other hand, wireless- based access solutions offer portability and flexibility to users, but they do not possess abundant bandwidth at lower microwave frequencies or have the difficulties to transmit longer distance at the millimeter-wave frequencies because of high attenuation in the air. To make full use of the huge bandwidth offered by optical fiber and flexibility features presented via the wireless, radio-over-fiber (ROF)-based optical-wireless networks have been considered the most promising solution to increase the capacity, coverage, band- width, and mobility in environments such as conference centers, airports, hotels, shopping malls - and ultimately to homes and small offices [9] [10].

The concept of ROF refers to the merging use of two conventional technology worlds: radio frequency (RF) for wireless and optical fiber for wired transmission. Long-range metro or wide-area access links are provided by optical fiber and links to end users are accomplished by RF wireless [11]. As shown in Fig 2.6 below, a typical ROF system consists of a Central Office, optical fiber network, remote passive node, and a large number of base stations (BSs). ROF systems perform all switching, multiplexing, signal generation and processing at the Central Office. An optical fiber network is used to transparently deliver the radio signals to multiple remote nodes (RN) and then to antenna BSs and end users [12]. The use of optical fiber to distribute RF signals to the BSs also offers better coverage and higher transmission performance because of low loss and immunity to electromagnetic interference of fiber. The typical distances between the CO and the BSs are 10-25 km, where each of the BS serves a picocell covering the distances of tens of meters. The prime benefit of ROF systems is the super- broadband services provision with high flexibility.

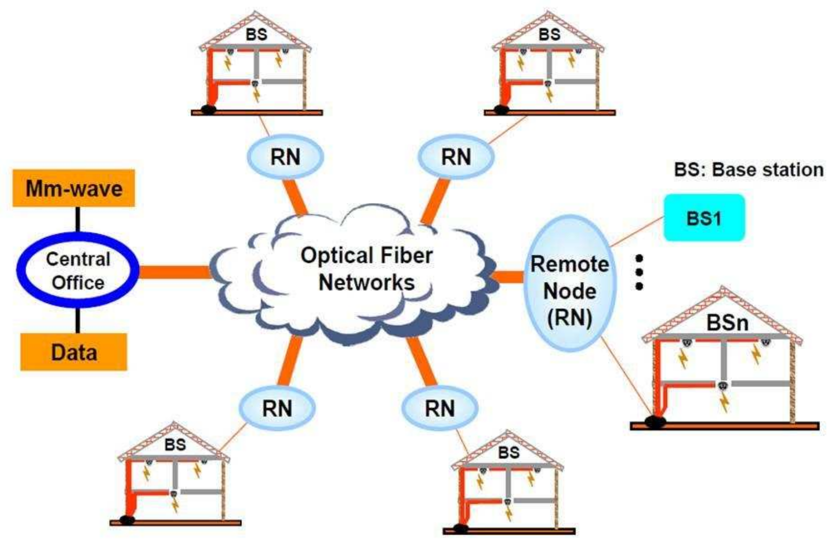

Fig 2.6: Visual representation of Radio-over-Fiber network. Courtesy: Z.Jia [2]

Comparative analysis

In the previous sections we have considered some of the different transmission schemes that are available. We shall now proceed to state the reasons why we think that 60GHz/1550nm RoF scheme is the best suited for the given set of applications. We firstly note that we have to transmit uncompressed HD video and images over a few feet. Also we intend to have the same setup in several adjacent rooms, thus necessitating frequency reuse. Since these applications are critical and the cost of failure to detect too high, monetary factors are not really important. These requirements are not met by ZigBee, Bluetooth or WiFi. All these systems are low bit rate systems that cannot support uncompressed HD transmission. Also in the case of WiFi, frequency reuse is not possible due to the range of transmission. These systems are primarily designed to minimize costs and not to provide guaranteed signal delivery. While UWB might be able to provide the necessary bandwidth using multilevel techniques like QAM (Quadrature Amplitude Modulation) and MPSK (Mulitple Phase Shift keying), it suffers from low range and interference. Also since the failure of standardization of UWB, it is difficult to use this band for such purposes. The limitations of using only mmWave or only fiber based technology are evident. Thus for the desired application, 60GHz Radio-over-Fiber technology is the ideal technology. This intuition is further confirmed by the demonstrations performed at the Optical Networking Research Group here at Georgia Tech. The first field demonstration involved cross campus unidirectional HD transmission using discrete Radio-over-Fiber Technology [13]. In the second experiment in building bidirectional super-broadband 60GHz RoF system using integrated transceiver [14] was demonstrated.

Summary

In this chapter, we have attempted to provide a basic introduction to the field of Broadband Access Networks. We briefly introduced the concept of wired networks. We then discussed in some detail the various types of wireless protocols and their limitations. The wireless channel model for the 57-64 GHz band was explained and its usefulness to our network was discussed. We shall now see the specific issues pertaining to our network and the advantages and limitations of various approaches to solving those problems.

CHAPTER 3

PROBLEM STATEMENT

Introduction

In the previous chapter we studied the properties of 60 GHz RoF transmission. We also gave a brief introduction to the properties of the 57-64 GHz band. We also discussed two demonstrations of the 60 GHz RoF technology. These topics fall under what is called the ‘Physical Layer’ of the OSI protocol stack.

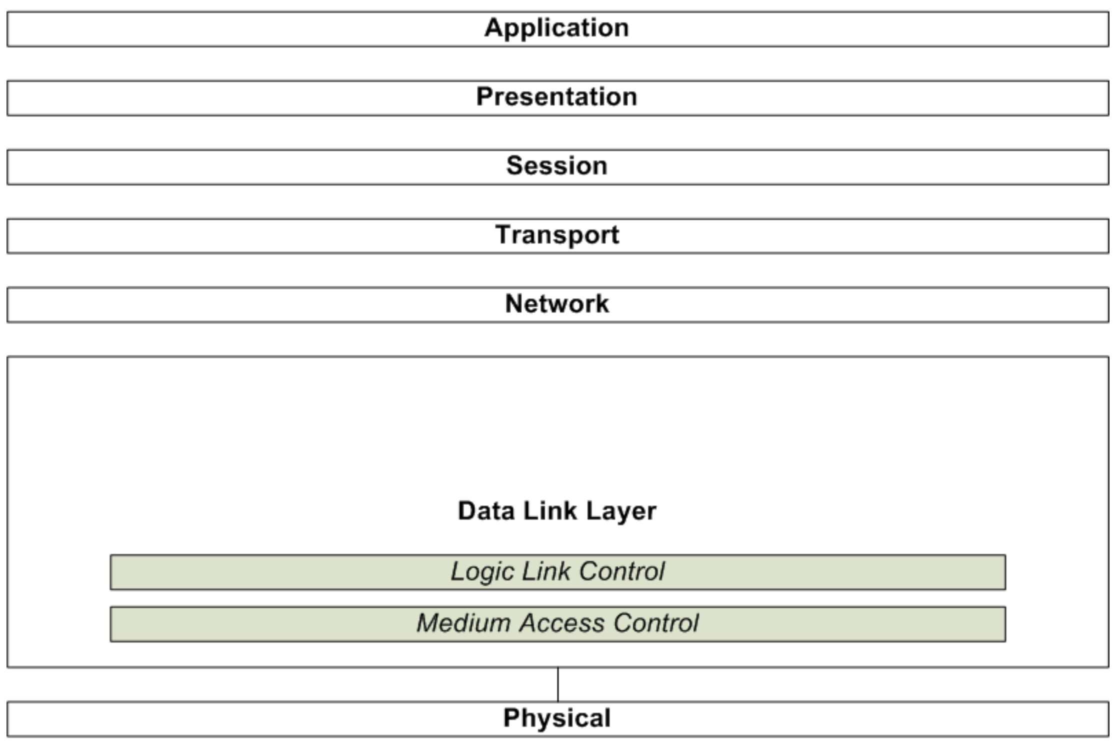

Fig. 3.1: OSI protocol stack showing different layers with special emphasis on the Data Link Layer. The Link Layer in turn is divided into the LLC (Logic Link Control) sublayer and the Medium Access Control sublayer.

As shown in Fig 3.1 the Physical Layer (often termed PHY) is the first and lowest layer in the seven-layer OSI model of computer networking. OSI stands for Open System Interconnection which is an abstract description for layered communication protocol design. It divides the network architecture into 7 layers as shown in Fig 3.1.

The Physical Layer consists of the basic hardware transmission technologies of a network. It is a fundamental layer underlying the logical data structures of the higher level functions in a network. Due to the plethora of available hardware technologies with widely varying characteristics, this is perhaps the most complex layer in the OSI architecture. The Physical Layer defines the means of transmitting raw bits rather than logical data packets over a physical link connecting network nodes. The bit stream may be grouped into code words or symbols and converted to a physical signal that is transmitted over a hardware transmission medium. The Physical Layer provides an electrical, mechanical, and procedural interface to the transmission medium. The shapes and properties of the electrical connectors, the antenna beam patterns, the frequencies to broadcast on, the modulation scheme to use and similar low-level parameters, are specified here.

The Data Link Layer is Layer 2 of the seven-layer OSI model of computer networking. The Data Link Layer is concerned with local delivery of frames between devices on the same network as shown in Fig 3.1. The DLC layer is further subdivided into two sublayers:

Logical Link Control sublayer

The uppermost sublayer is Logical Link Control (LLC). This sublayer multiplexes protocols running atop the Data Link Layer, and optionally provides flow control, acknowledgment, and error notification. The LLC provides addressing and control of the data link. It specifies which mechanisms are to be used for addressing stations over the transmission medium and for controlling the data exchanged between the originator and recipient machines.

Media Access Control sublayer

The sublayer below it is Media Access Control (MAC). This refers to the sublayer that determines who is allowed to access the media at any one time (usually CSMA/CD). It also deals with frame structure with MAC addresses inside.

Proposed Network Characteristics

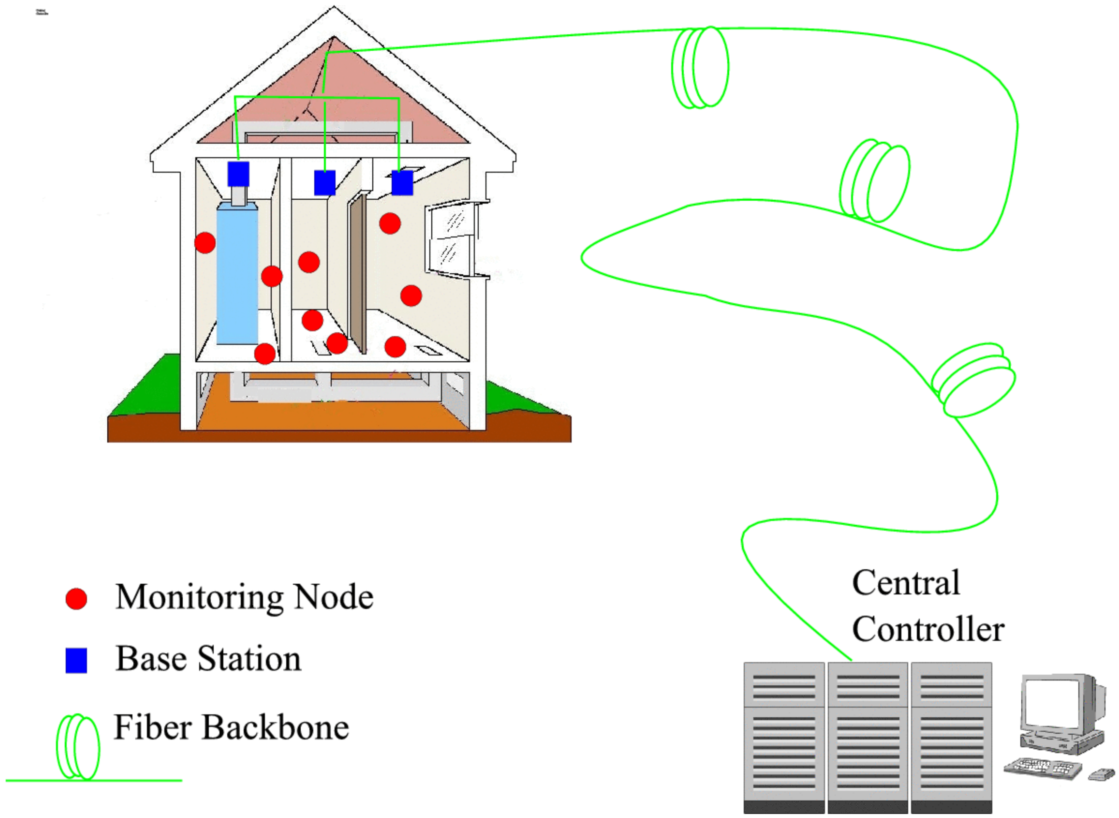

Fig. 3.2: Schematic of the Proposed Network

The Fig 3.2 shows a schematic of the proposed network. It consists of a set of monitoring nodes which generate the data. This data is then transmitted wirelessly using the 57-64GHz band to the Base Station. In the Base station, the Electrical-to-Optical conversion takes place and the signal is now transmitted by means of the fiber backbone to the Central Controller. All data processing is assumed to take place at the Central Controller.

This is significantly different from most sensor networking applications where the processing mostly takes place at the node itself or at the Base Station (which in some sensor networks is also called a Clusterhead [16]). This is the reason why we use the term “monitoring node” instead of sensor node. This distinction is also used to emphasize the difference in power requirements. Conventional sensor networks emphasize a low power requirement. They also perform data acquisition based on events whose occurrence is resolved at the node itself. Generally, sensors are idle for most of the time. We instead are focusing on monitoring applications which implies that there is a continuous stream of data emanating from the nodes that has to be transmitted to the Base Station and from there onwards to the Central Controller. Such applications entail critical data, failure to obtain which may result in catastrophic failure.

One of the consequences of this is that the nodes are aware of the destination of the data. Also they always have some data to transmit. The consequence of this is that the load conditions are high traffic load conditions. This means that there are no sudden periods of activity followed by long periods of inactivity. This implies that the nodes and the Base Station need to be ready to transmit or receive data.

This implies that the Base Station and the nodes are energy unconstrained. The network is assumed to be an infrastructure network, i.e. a number of fixed Base Station connected through a fiber backbone. Such a topology can be easily envisaged in smart building applications, where the Fiber-to-the-Home and power cabling exist.

The uplink and downlink wireless channels are assumed to be identical. The same radio frequency and the same MAC protocol apply for both directions.

At the time of writing, no devices that perform these functions are known to exist. We however can envisage what capabilities the devices must possess in order to enable such a network to function. We hence now discuss some of the details of the inner working of such devices.

Monitoring Node Behavior Description:

As can be seen from the Fig 3.3, the monitoring node comprises of the following components. Firstly, we have a Sensing element. This could be a thermal imaging camera, a CCD camera or any other such device capable of generating HD video or images. The responsibility of transmitting the data rests on the 60 GHz Radio transceiver. Transmission takes place only when the processor permits transmission after receiving instructions to do so from the base station. This is to avoid any synchronization errors. Since most of the processing takes place at the Central Controller, the on-chip or on-board processor has the principal responsibility of ensuring that the protocol is followed.

The storage primarily stores the physical addresses and other protocol related details. It can also be used to store the data generated. However, this is not feasible to store such data for over a few seconds due to the sheer volume of data generated. The power source supplies power to all components in order to ensure proper functioning.

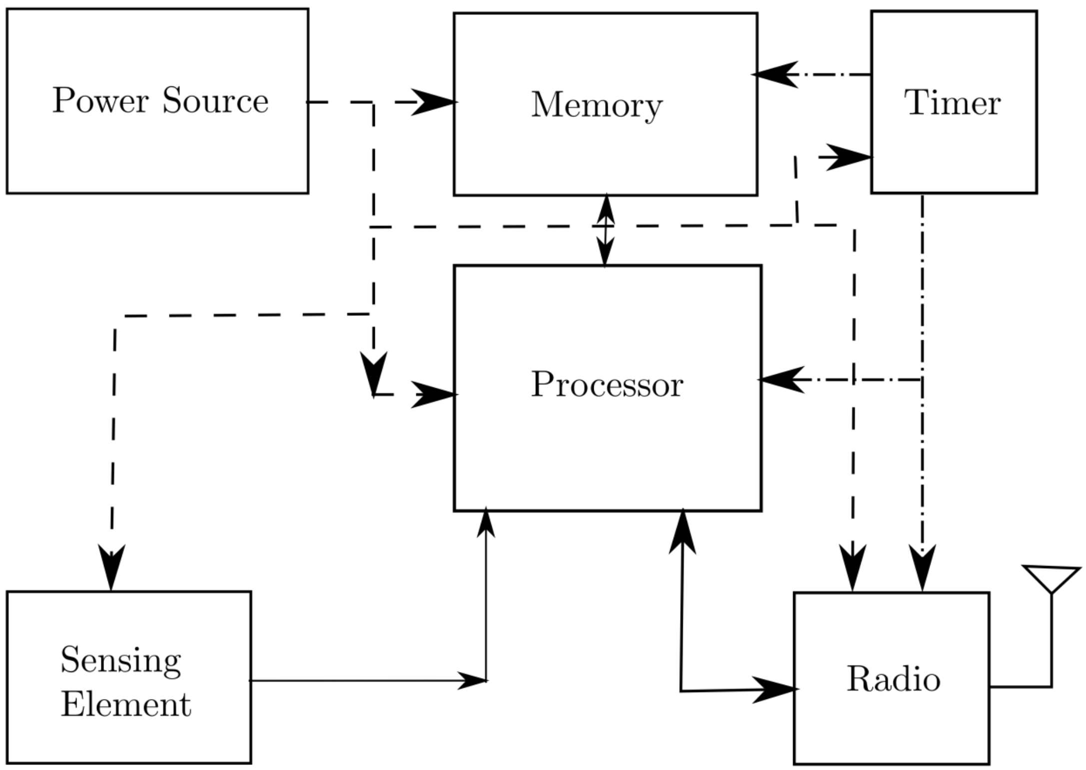

Fig.3.3: Block Diagram Representation of the Monitoring Node

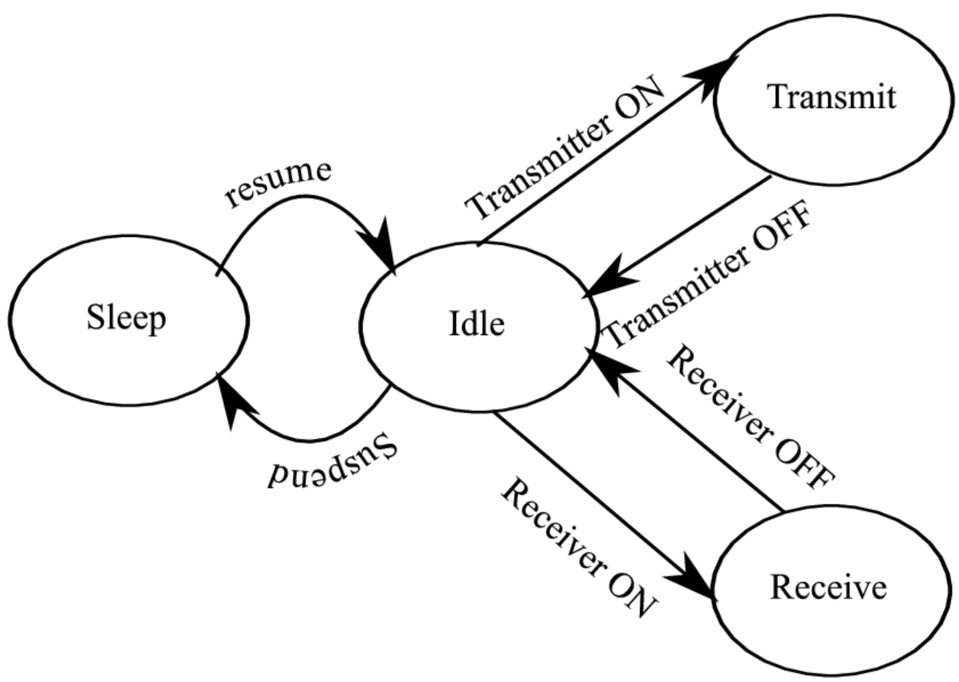

Fig.3.4: State transition representation of the Monitoring Node Behavior

Node State	Processor	Sensing element&ADC	Xceiver	Storage
Sleep	Inactive	Inactive	Inactive	Inactive
Rx	Active	Active	Active	Active
Tx	Active	Active	Active	Active
Idle	Inactive	Inactive	Active	Inactive

Table 3.1: Description of each state in terms of the behavior of the individual blocks of the Monitoring nodes

As can be seen in Fig 3.4 the node can exist in four states: Sleep, Receive, Transmit and Idle. Table 3.1 shows that the Sleep state applies when all components are switched off. This is seldom used if the application is critical as the startup times for all components may be significant. In the Receive and Transmit states, all the components are active, receiving instructions on behavior or transmitting data. The Idle State is reached whenever all components except the transceiver are switched off. This is used whenever the node is not transmitting or receiving. Its purpose will be clarified when the protocol is explained.

Base Station Behavior Description:

As can be seen from Fig 3.5 the base station comprises of the following modules. Firstly, we have the processor. While the functionality of this module is similar to that of the monitoring node, it is far more powerful as it has to control transmission and reception with all the nodes under its control whilst also maintaining overall network functionality by communicating with the central controller by receiving and transmitting data through the fiber.

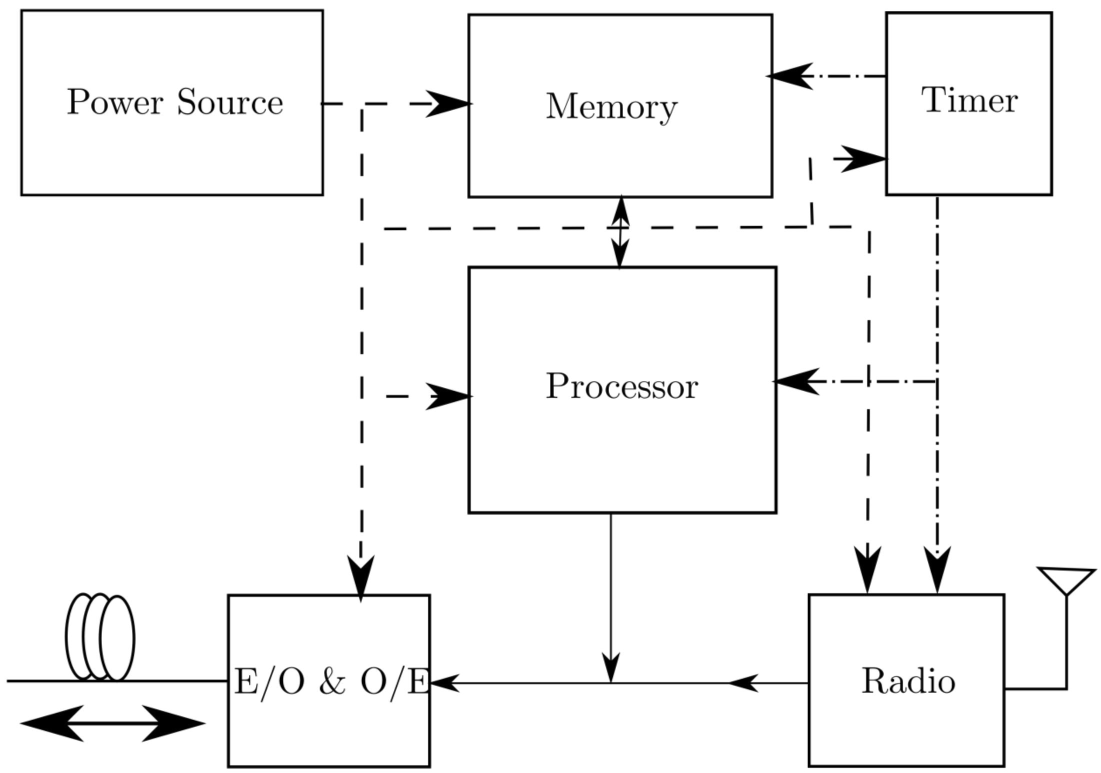

Fig.3.5: Block Diagram Representation of the Base Station

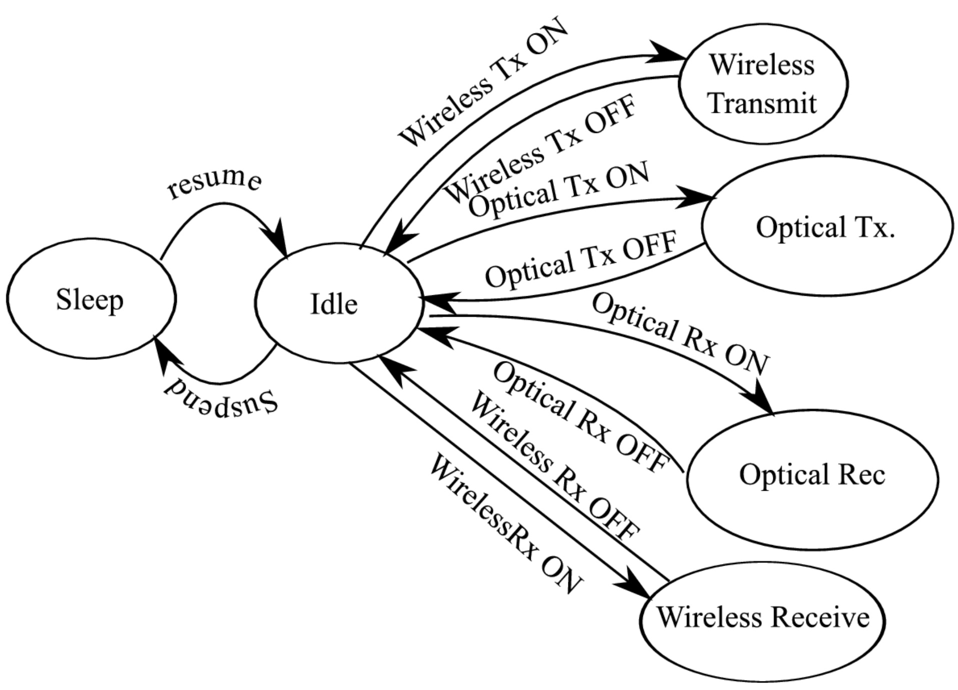

Fig.3.6: State transition representation of the Base station Behavior

BS state	Processor	O/E &E/O	Radio	Storage
Sleep	Inactive	Inactive	Inactive	Inactive
Idle	Inactive	Active	Active	Inactive
WirelessXmit	Active	Inactive	Active	Active
WirelessRec	Active	Inactive	Active	Active
OpticalXmit	Active	Active	Inactive	Active
OpticalRec	Active	Active	Inactive	Active

Table3.2: Description of each state in terms of the behavior of the individual blocks of the Base Station

In order to collect data from the node and transmit it to the central controller, there needs to be a module that performs Electrical-to-Optical and Optical-to-Electrical conversions. This implies that in the state machine diagram as shown in Fig. 3.6 the Transmit and Receive modes are bifurcated into the Wireless-Transmit and the Wireless-Receive and Optical-Transmit and Optical-Receive modes depending upon whether the radio or the O/E&E/O module is active as illustrated in Table 3.2. The purpose of the Storage module here is to store the Medium Access Table (see Chapter 6) and additional protocol details. Note however that the Storage unit does not save any data. This is done in order to simplify the design. The timer is absolutely vital and is kept ON at all times. It maintains synchronization of communication amongst all the monitoring nodes whilst also communicating data systematically to the Central Controller. The quality of the crystal used for this is recommended to be very high. In order to maintain synchronization it is also necessary for clock recovery of the signal to take place.

The states that the Base Station can exist in are shown in the state transition diagram in Fig 3.6. The states are correlated with the hardware states in Table 3.2. The Sleep and Inactive states have the same purpose as in the monitoring node.

Purpose of MAC Protocols

Owing to the constraints of transmitting uncompressed HD video and images in real time for monitoring applications, it is desirable that the proposed MAC protocol enable reliable, error-free transmission without need for retransmission.

The function of the MAC protocol can be broadly divided into three categories [17]:

i. Channel Access Policies

ii. Scheduling and Buffer Management

iii. Error Control

Channel access policies deal primarily with regulating node access to the channel. This is important if we have to prevent collision and retransmission which are a source of energy wastage and of additional delay. Scheduling deals primarily with delay bounds and queuing disciplines. In order to obtain a working solution, this development has to be done in conjunction with the channel access policy and the two have to be seamlessly integrated. This shall be the primary focus of this Thesis.

Link layer error control deals primarily with the difficulties of streaming real time multimedia data over a monitoring network in order to meet the QoS requirements of a video stream given the unreliability of the wireless channel. The unreliability of the wireless channel is caused on account of multi-path fading and shadowing at the physical layer and collisions at the MAC layer at lower frequency bands. A well designed channel access policy shall prevent the latter. The former can be solved by suing either an ARQ (Automatic Repeat Request) or FEC (Forward Error Correction). ARQ is inefficient in handling latency as it causes the same data to be transmitted twice. It is clearly unfeasible for applications requiring real time delivery of multimedia content. Different FEC schemes have been proposed for video streaming [18,19,20].

Channel Access Policies

Contention Based Protocols

In these methods, the resources are not assigned to individual nodes. Whenever a node has data to send, it must contend for access to the channel with other nodes that have data to send. Therefore, collisions can occur when two nodes think that they have access to the channel at the same time. This, in turn, will reduce overall throughput. Hence it is necessary to minimize collisions (and hence maximize throughput) while maintaining fairness in the use of resources among all the nodes.

Carrier Sense Multiple Access

Carrier-sense multiple access (CSMA) is one such random-access approach. Using CSMA, when a node has data to send, it listens to the channel to try to determine if any other node is currently transmitting. The flowchart is as shown in Fig 3.7

Using carrier-sense will reduce collisions, but it cannot guarantee that collisions will not occur. For example, there is a small (but nonzero) probability that two nodes will sense the channel at the same time, both decide that the channel is free for transmission, and both transmit data at the same time, causing a collision of both data messages. The more likely collisions will occur because the transmitting node cannot "hear" everything that the receiving node can hear. In this case, the transmitting node assumes that the channel is free for transmission, while the receiving node is busy receiving data from another node. This will cause a collision at the receiving node, which will not be able to receive data from either transmitting node. This is known as the hidden terminal problem. The main problem is that collisions occur at the receiver but need to be detected at the transmitter. In a wired network, the transmitter and receiver hear the same message and the transmitter can detect a collision at the receiver. In a wireless network, on the other hand, due to the propagation loss of the radio signal, the transmitter cannot always hear the same message the receiver hears.

Newer randomized protocols use pre- transmission messages (e.g., request-to-send (RTS) and clear-to-send (CTS)) to further reduce the risk of collision. The transmitting node sends out an RTS message, and the receiving node must send out a CTS message before the transmitting node can send any data. All nodes listen for CTS messages. Once a CTS message is heard, all other nodes know not to transmit their own RTS messages on the channel until the current transmission is complete. This further reduces collisions, at the expense of increased overhead and energy dissipation since nodes need to receive all messages to obtain the CTS messages. In addition to collisions, there may be packet losses if the transmitter has to back off too long and the data are time-sensitive. There can also be buffer overflow if the node has too many packets to send and cannot access the channel, resulting in lost data. Randomized protocols have the advantage of being simple to implement, requiring no knowledge of the network topology or global control, and they are easy to configure. However, we believe that their applicability to multimedia transmission is limited owing to the following reasons [17]:

- The primary concern in the protocols of this class is saving energy, and this is accomplished at the cost of latency and by allowing throughput degradation.
- Coordinating the sleep–awake cycles between neighbors is generally accomplished though schedule exchanges in light of the ongoing high data rate video/audio messaging.
- Such an operation could well lead to strong jitters and result in discontinuous real-time playback.

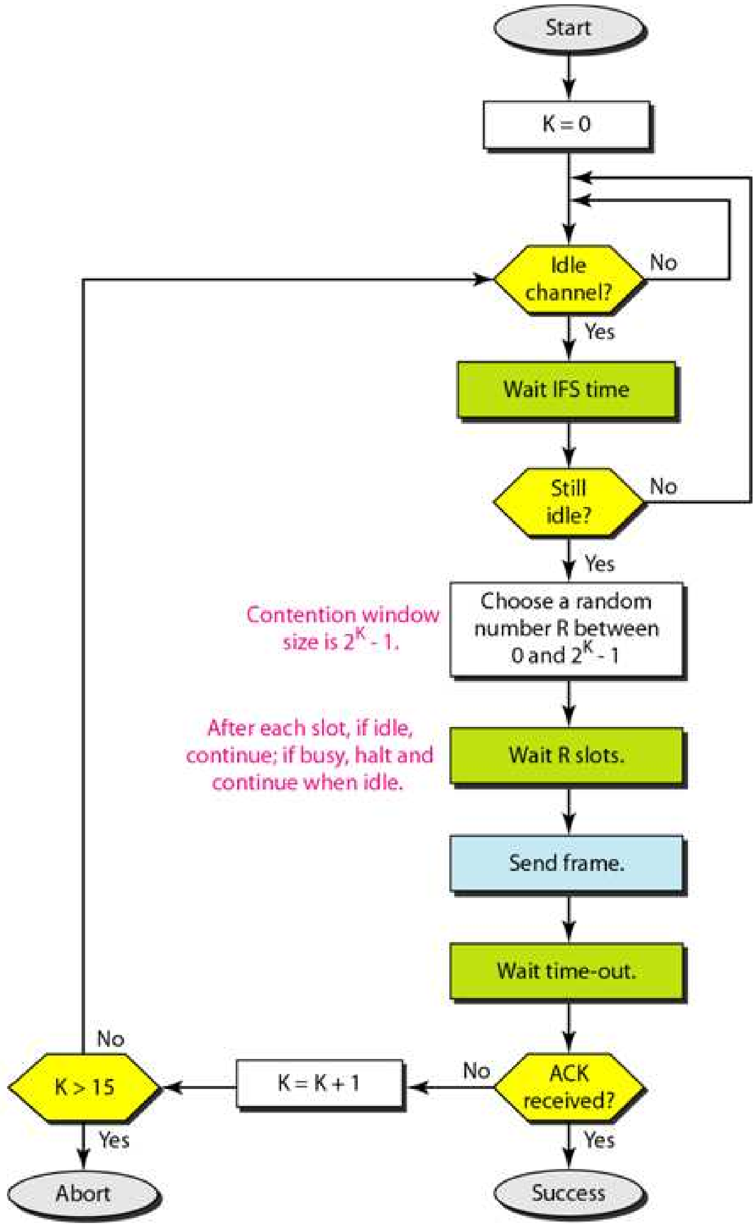

Fig. 3.7: Flowchart for CSMA Protocol. Courtesy: B. Forouzan, Data Communication and Networking 4e [15]

Contention Free Protocols

We have hitherto considered Contention based protocols i.e. protocols in which the nodes contend with each other for transmission time. The principal drawback of this scheme is that collisions can occur i.e. two or more nodes could simultaneously access the channel. This necessitates retransmission, which increases delay. This is highly unsuitable for high bit rate high definition video or image transmission. Also in case of critical applications, this could lead to problems as vital data may be lost. Hence we consider cases where the channel is allocated to different nodes in a fixed fashion. Thus there is no contention for resources and the drawbacks are avoided. Most contention free protocols are based on allocating either time or frequency amongst all nodes giving rise to either Time Division Multiple Access or Frequency Division Multiple Access schemes.

Frequency-Division Multiple Access (FDMA)

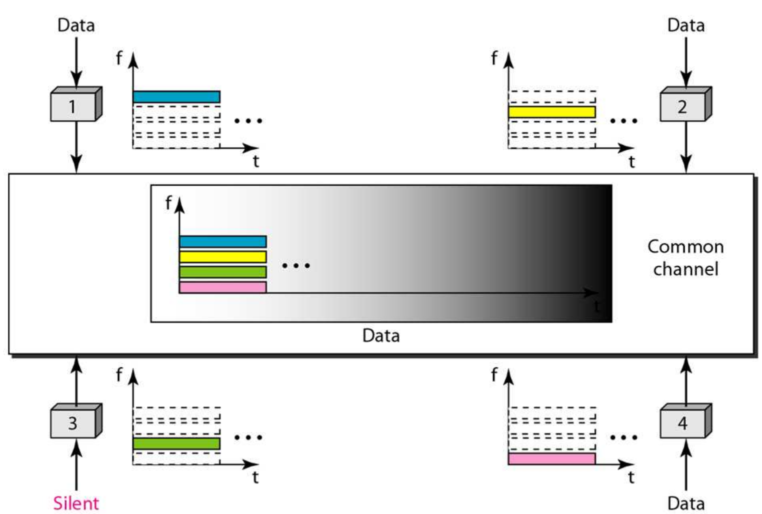

Fig.3.8: Representation of FDMA. Courtesy: B. Forouzan, Data Communication and Networking 4e [15]

In FDMA as represented in Fig 3.8, the bandwidth is divided into slices such that each user gets a unique section of bandwidth in which to transmit data. If there are N nodes that must share the BW bandwidth, each node gets a frequency slice of size BW/ N in which to transmit [15,16].

The principal advantage of this scheme is that because no node is supposed to transmit in the bandwidth slice given to another node, there are no collisions between transmissions. Transmission is continuous in FDMA, reducing the number of guard and synchronization bits needed compared to TDMA, thereby decreasing overhead.

The disadvantages are FDMA may require guard bands to ensure transmissions do not overlap in frequency). However, FDMA requires that the transmitter hardware be on at all times, increasing the energy dissipation compared with a burst transmission protocol such as TDMA. In addition, FDMA requires good filtering to ensure that energy transmitted in the neighboring slices of bandwidth do not interfere with the transmission.

Time Division Multiple Access or Scheduling Based Protocols

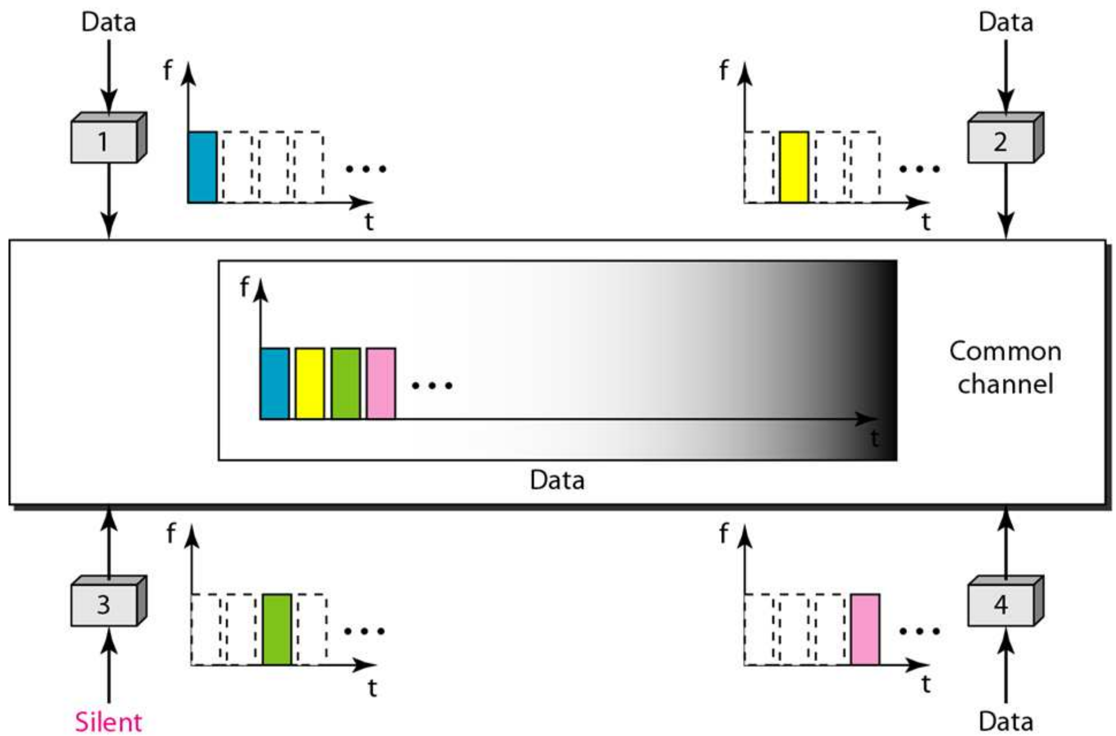

Fig.3.9: Representation of TDMA. Courtesy: B. Forouzan, Data Communication and Networking 4e [15]

In TDMA, as represented in Fig 3.9, time is broken into frames, and each node is given a specific time-slot within the frame in which to transmit its data. During this time-slot, no other node should access the channel, so there are no collisions and the throughput is equal to the total data transmitted by each node. Assume there are N nodes that have data to transmit and the time for each frame is t_f

and the channel bandwidth is BW. Each node will get $t_s = t_f / N$ seconds in which to transmit data. [15, 16]

Limitations of current Schedule Based Protocols

Terms and Definitions:

Active Range: In a Radio-over-Fiber based network, we use this term to denote the distance between the Monitoring node and the nearest Base Station. In wireless transmission, it is the lowest value one-hop distance

Passive Range: In a Radio-over-Fiber based network, we use this term to denote the distance between the Monitoring node and the Central Controller. In wireless networks, this would correspond to the source to destination distance.

There exist some limitations in the main schedule-based protocols that currently exist that make it difficult to use them for our application. This stems from two primary reasons. Firstly, most of the current protocols are designed for low bit rate systems operating at relatively low frequencies, and have a fairly long active-range of a few hundred meters or more. This is significantly different from our application where we are using high bit rate transmission at millimeter wavelengths for short active-range transmission. Also, while most other protocols are designed for strictly wireless systems, we are exploiting the benefits afforded by the recent convergence in wireless and optical technologies, to provide high-def video and image data. Some of the benefits of this technology are longer passive-range, significantly higher bandwidth and moderate ability to move the monitoring nodes. Some of the principle limitations however are the low active range and the fact that the Base Station being attached to the fiber is fixed. However this also means that we can provide for a non-storage type electricity supply to the Base station and hence the energy consumption by the Base Station is less of a concern.

We shall now briefly outline the major schedule-based protocols for wireless system and state their limitations.

LEACH**:** LEACH stands for **L**ow **E**nergy **A**daptive **C**lustering **H**ierarchy [21], [22]. It assumes a dense sensor network of homogeneous, energy-constrained nodes, which report their data to a sink node. The nodes are partitioned into clusters and each cluster has a dedicated node, called the Clusterhead, which is responsible for creating and maintaining the TDMA schedule. Data is exchanged only between the node and the Clusterhead which then transmits the data to the sink node. The relatively larger distance between the sink node and the Clusterhead implies that a significant energy is spent by the Clusterhead. LEACH addresses this issue by rotating the Clusterhead amongst nodes that have higher energy. This results in the following serious limitations. Firstly rotation of Clusterheads implies that the clusters have to be reformed frequently, which is a time variable process. Also this needs global timing synchronization. Besides during cluster reformation, some nodes might get left out. Another limitation is that the coverage area is quite small as the Clusterhead must have enough energy to transmit to the sink node. This scheme also has a low BER. We attempt to address the above issue in the following fashion. The Base Station is kept fixed and is communicates with the Central Controller by means of fiber, instead of a purely wireless link. It is given a permanent source of power. This implies that power consumption by the Base station need not be a major concern; hence there is no need to rotate the Clusterhead or reform clusters. Also we significantly increase the passive range by using a fiber-based technology and significantly lower BER.

SMAC-S**:** SMAC-S stands for **S**elf-organizing **M**edium **A**ccess **C**ontrol for **S**ensor networks [23], [24]. It essentially combines neighborhood discovery and assignment of TDMA schedules. The spectrum is subdivided into many channels and each node can tune its transceiver to an arbitrary one. Alternatively many CDMA codes have to be available. Clearly, both approaches are not feasible for high bit rate transmission at millimeter wave frequencies and lead to significantly higher costs. It also assumes node to node communication which is not what we are trying to achieve.

TRAMA**:** TRAMA stands for **TR**affic **A**daptive **M**edium **A**ccess protocol [25]. In this protocol, the schedules are constructed by all the sensors when needed in a distributed fashion. Time is divided into random access periods followed by scheduled access periods. The protocol is implemented in three stages. The first protocol is called the neighborhood protocol, which is executed in the random access phase. In this case, each node learns about its two hop neighborhood. All node transceivers are active during this phase. The next protocol is called the schedule exchange protocol, here a node transmits its current schedule and also picks up those of its neighbors. The final protocol occurs in the scheduled access phase and determines when a node can go to sleep. This is called the adaptive election algorithm. As can be evidenced from the previous description, the above protocol while being highly adaptive is exceedingly complicated and needs significant computation and memory requirements in each of the sensor nodes as the algorithm is distributed. Also as been reported in [25], the energy savings of this protocol depends upon the load situation.

Need for a new protocol

Besides the above limitations, schedule based protocols in general suffer from some limitations. Firstly, all schedule based algorithms are variants of the basic TDM scheme. This implies that all schedule based algorithms need timing synchronization. We shall see how this issue is solved in the next chapter. Also, requirements are not the same at all times. When an emergency occurs, it might be necessary to obtain data from a single node or a few nodes. The data obtained from other nodes may not be relevant. Adapting schedules according to varying requirements is difficult. We attempt to accomplish the same using three modes for our MAC protocol. We shall elaborate on this in the next chapter as well. We shall also study the performance of our protocol and seek to further understand its behavior

CHAPTER 4

PROPOSED SCHEME

Introduction

In the previous chapter we have seen that conventional schedule based protocols are insufficient to meet the requirements of our network. These limitations have the following sources:

1. **High Bit rate:** Conventional MAC protocols are designed for low bit rate applications. Typical values range from a few kbps to a few Mbps. On the contrary we have to transmit HD video and images which could take several Gbps of transmission rate. Also the low bit rate implies that most of the processing can be done at the node or the base station. There is no need to transmit raw data to the Central Controller for processing.
2. **Delay critical nature:** This implies that it is possible to design systems that respond only in the case of an event. This results in energy savings. Also since most of the nodes have battery operated power sources which have to last for a long time, the emphasis is on energy conservation. On the other hand we are transmitting video images. Preserving the real time nature of these transmissions is absolutely vital. Hence our operations are delay critical
3. **Flexibility:** In conventional sensor networks, the type of data transmitted is the same under all conditions. Also the data for a whole picocell is generally aggregated before transmission. In our case, we have a few very high bit rate video/image generation units. This implies that there does not exist the

possibility of data aggregation. Thus in the case of an emergency, it becomes imperative to be able to modify the MAC protocol so as to obtain data from one node only. After the emergency has ceased to be, we must be able to resume normal operations. Also not all nodes are equally critical. We must be able to fix the transmission time of each node independently

Proposed Protocol

We attempt to overcome the previously mentioned limitations by proposing the following protocol. As indicated previously the 57-64GHz band is divided into 4 channels. A node is allocated a specific channel. The overall time is divided into slots. Since failure cannot be deemed acceptable, we include a mode called the Icarus mode, as shown in Fig 4.2, during which a single node that is monitoring a critical situation shall be allocated all time slots. We also supply the transmission time to the node via the Base Station, as shown in Fig 4.1. This implies that different nodes can be given different number of time slots. Also the time slots allocated to any specific node can be altered after installation or at any time we deem necessary, thus improving flexibility. Also this enables us to install more nodes in the future by simply changing the time allocated to the existing nodes. This improves scalability. We now shall develop the timing diagrams and behavior of this protocol.

Steady State Timing

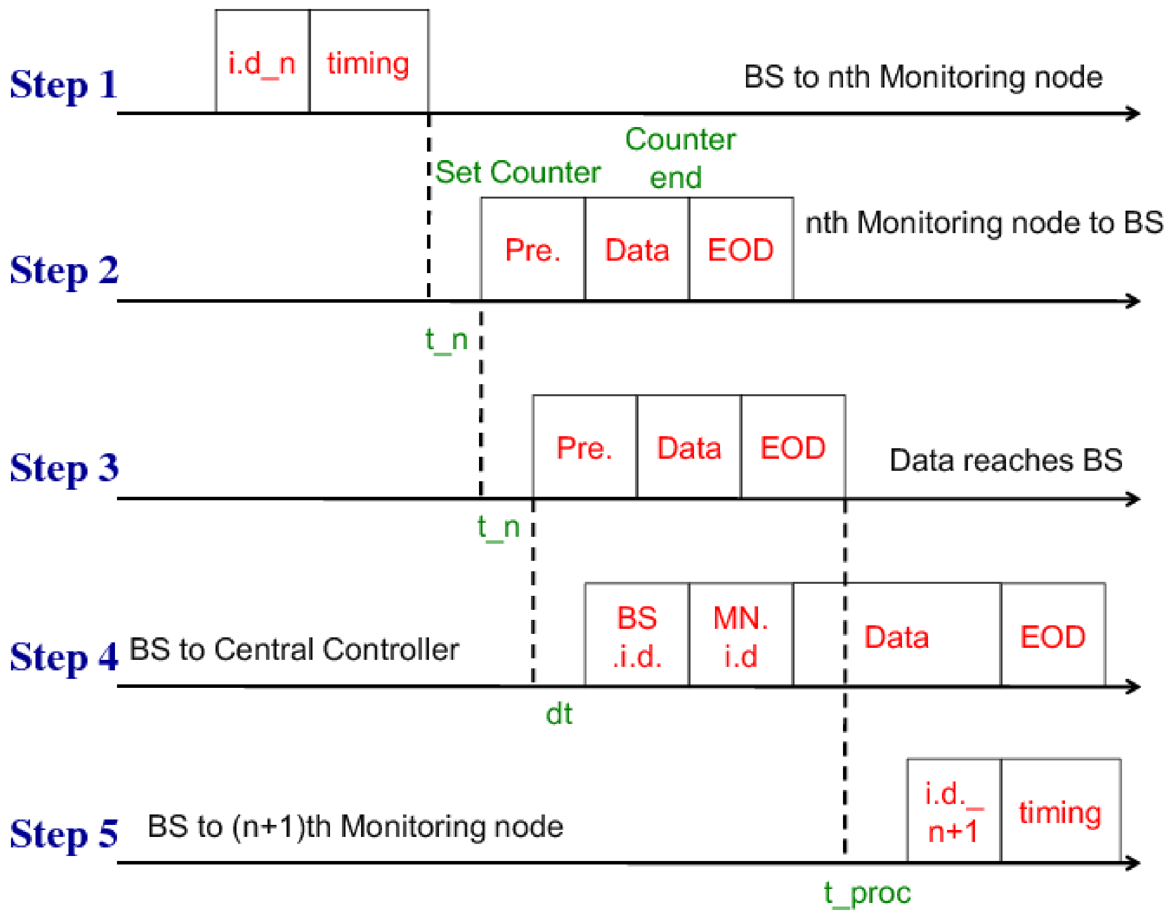

Fig.4.1: Timing Diagram for the steady state operation

Our protocol is based on TDMA scheme like all the other schedule based protocols. This implies that time is divided into small slots. Transmission may take place only during a unique time slot, i.e. the transmitter and the receiver have to agree upon unique time slots for transmitting and receiving information. If time slots overlap, then collisions will occur. This would result in additional delay caused by retransmission of the same data and poorer channel utilization. Thus timing synchronization is needed. It is also important to remember that the on chip clock is non ideal. We solve this problem by having the base station tell the node when to begin transmission and only after the node has received the signal can it transmit information. The other additional benefit of letting the base station transmit the timing data to the nodes is that we can then implement non uniform TDMA, wherein time slots of different widths may be assigned to different sensors depending upom our requirements. This greatly improves flexibility.

Upon receiving the timing information, the node begins transmission of data. The timing data that was transmitted in the previous step is used to set the counter to the value that the Base Station wants. The counter is decremented. When the time is up, the node attaches a prearranged End of Data (EOD) bits. This informs the Base Station that the node has stopped transmission. This along with the next step prevents the collision of data from adjacent nodes. Note that two nodes are said to be adjacent if they occur consecutively on the schedule.

As shown in the Figure 4.1 after a certain delay, the Base Station receives the data. The Base Station then adds information such as the Base Station i.d. and the node i.d. Note that the addressing scheme used is relative. This utilizes the hierarchy inherently presents and simplifies the process of addressing. This data is needed if the Central Controller observes abnormal data and wishes to access the data from that particular node in Icarus mode. This is then transmitted by means of the fiber to the Central Controller.

When the Base Station receives and processes the EOD bits, it knows that the node has stopped transmitting. It then broadcasts the i.d. and the timing data of the next node.

Icarus Mode Timing

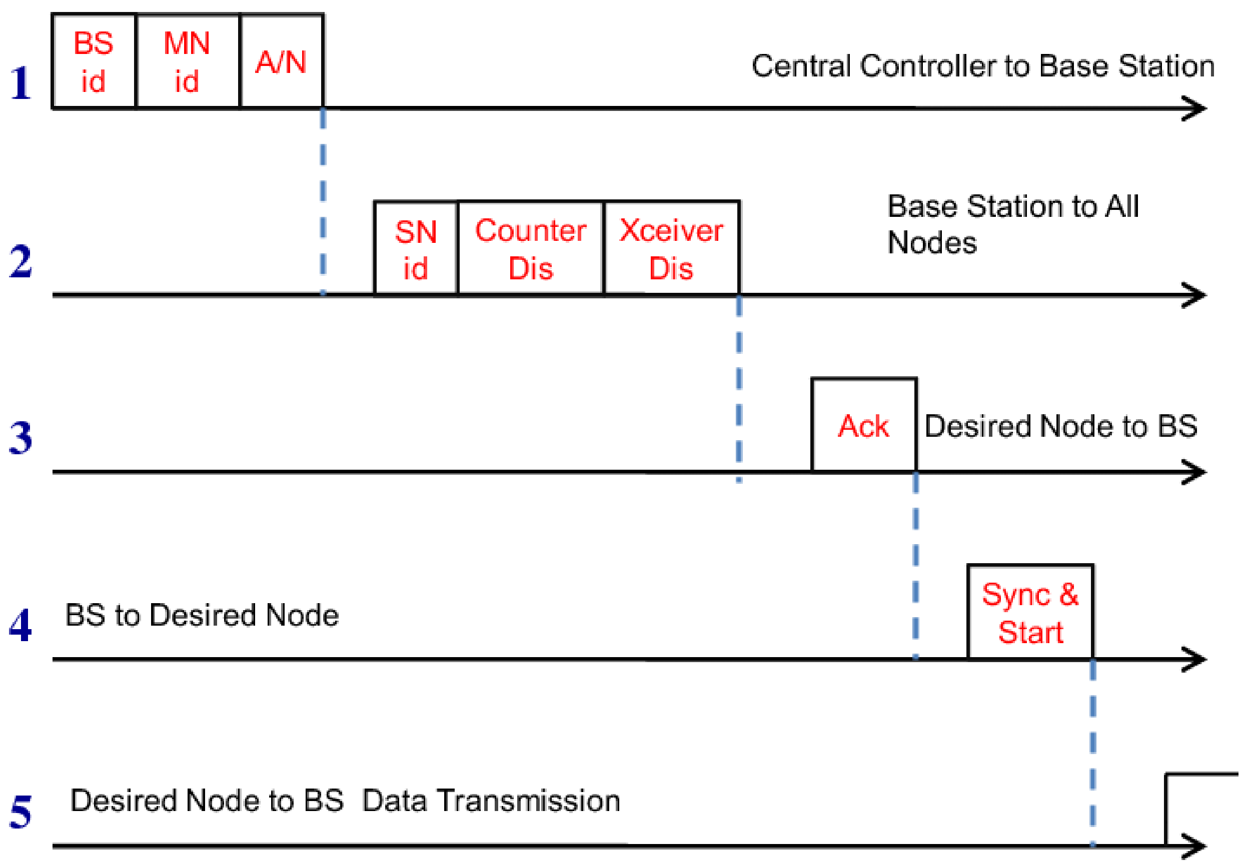

Fig 4.2 : Timing diagram of the Icarus Mode

One of the benefits of letting the Base station decide the timing schedules is that it is possible to vary the same without much extra effort. This gives rise to additional flexibility. In case an emergency occurs, it is possible to give as much time as deemed necessary by the Central Controller to a specific node. We call this mode of operation the ‘Icarus Mode’. Icarus is a character in Greek mythology. He is the son of Daedalus and is commonly known for his attempt to escape Crete by flight, which ended in a fall to his death. Daedalus fashioned two pairs of wings out of wax and feathers for himself and his son. Before they took off from the island, Daedalus warned his son not to fly too close to the sun, nor too close to the sea. Overcome by the giddiness that flying lent him, Icarus soared through the sky curiously, but in the process he came too close to the sun, which melted the wax and hence Icarus fell into the sea. This legend is frequently used a warning to not ignore crucial information that could possibly result in catastrophic failure.

Shown above in Fig 4.2 is the timing diagram of the Icarus mode of operation. When the Central Controller observes abnormal data, it transmits the i.d. of the node that it feels has abnormal data to the Base Station. The Base Station upon receipt of this information, waits till the end of the current cycle, and then broadcasts the i.d of the node along with a Clock Disable and Transceiver Disable signal. If the node matches its i.d. to the one being broadcast then it will disable the Counter, as it has to transmit data indefinitely till instructed otherwise by the Central Controller. All the other nodes whose i.d. does not match that of the broadcast i. d. shall disable their transceivers and go into sleep mode. The desired node then sends out an ACK (Acknowledge) packet to acknowledge that it has received the message and is willing to start transmission. Upon receiving the Start signal from the Base Station, it begins data transmission.

Resync Mode Timing

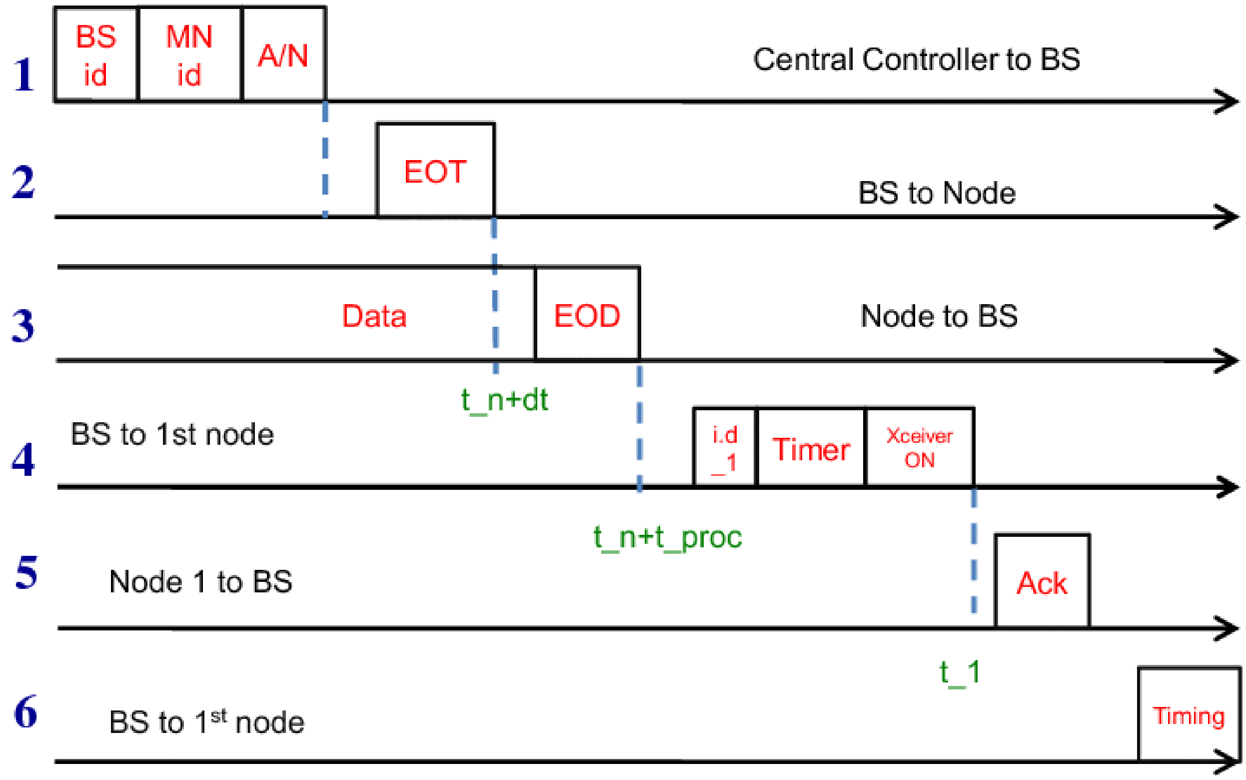

Fig 4.3: Timing Diagram of the Resync Mode

After the Central Controller has deemed it acceptable to return to normal operation, it is necessary to do so in a systematic fashion. Firstly, all operations for the other nodes have been disrupted. Secondly, the node in question has had its timer wiped out. We now proceed as shown in Fig 4.3. Firstly, the Central Controller sends the Base Station id and the node id to the desired base station. The base station after decoding this sends an End of Transmission (EOT) signal to the node. When the node receives and processes this, it sends out an End of Data (EOD) to the Base Station. When the Base station receives this it knows that the concerned node has ceased transmission. It then proceeds to resynchronize the nodes as follows. It sends a timer resync and transceiver ON signal to a node. When it receives and ACK it then sends the timing information and now communication proceeds as follows

State Transition Diagram

We attempt to represent the information stated above in a compact form in the form of a State Transition Diagrams as shown in Fig 4.4 and 4.5. This also helps correlate the behavior of the node and the base station more closely with the block diagram architecture provided in Chapter 3, Fig 3.3 and 5.5.

Monitoring Node

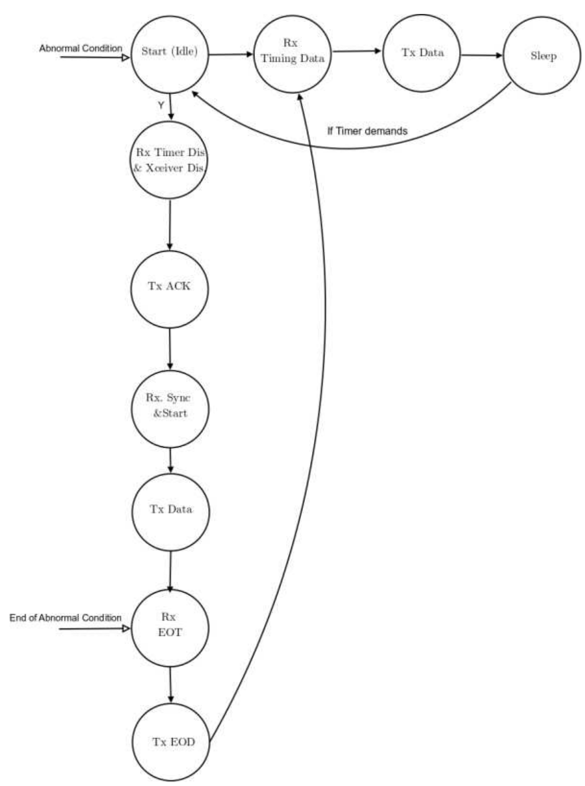

Fig. 4.4: State Machine Diagram describing the behavior of the monitoring node

Base Station

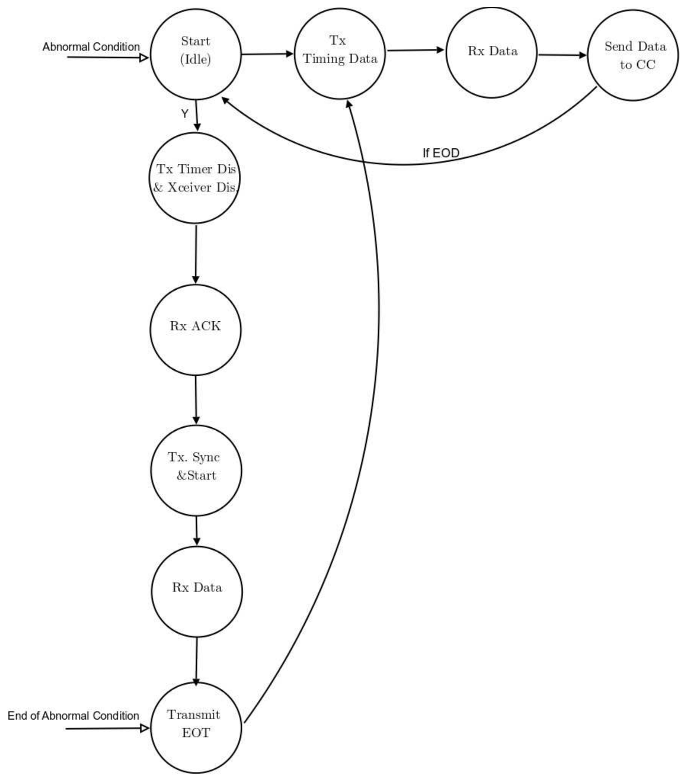

Fig 4.5: State Machine diagram describing the behavior of the Base Station

Simulation

Simulation Methodology

We attempt now to further our understanding of the protocol by performing a Monte Carlo Simulation. In order to obtain stable average parameters, it is necessary to perform as much iteration as possible. We perform the simulation in batches of hundred iterations. Once for every ten such batches, we assume that the Icarus mode occurs. This is assuming that there is a fairly high number of emergencies occurring roughly once every 25 to 30 seconds. Since, the hardware is not available we are designing for the worst case scenario. The time taken for the Icarus mode is randomly selected between 1 sec and 10 sec, which is fairly large. The average delay per iteration is then computed and plotted. The batch in which the Icarus mode shall occur too is randomly chosen.

Simulation Parameters

Average distance between node and Base Station = 5m

Time duration of data transmission = Time taken for transmitting one frame

Processing delay = 1 μ sec

We shall now attempt to justify the simulation parameters. As stated previously, the hardware needed to implement such a protocol has not yet been designed. This implies that we are designing for the worst case scenario. The average distance between node and base station is determined by loss. Since the speed of light in vacuum is $3*10^8$ m/sec, any increase in this distance upto 10 m would be negligible. We wish to demonstrate that the protocol overheads are minimal. Hence we have selected the smallest possible continuous transmission of data in order to obtain the worst case scenario.

Simulation Results

Several such iterations of transmission were carried out and two of those iterations have been plotted. We can see from the results in Fig 4.6 that the additional delays on account of the protocol are negligibly small (of the order of a few micro-sec) so as to not even appear on the graph. The primary source of delay is the data transmission itself. The large spike denote the occurrence of the Icarus mode. This is desirable as it implies that we have large channel utilization and that protocol overheads are small

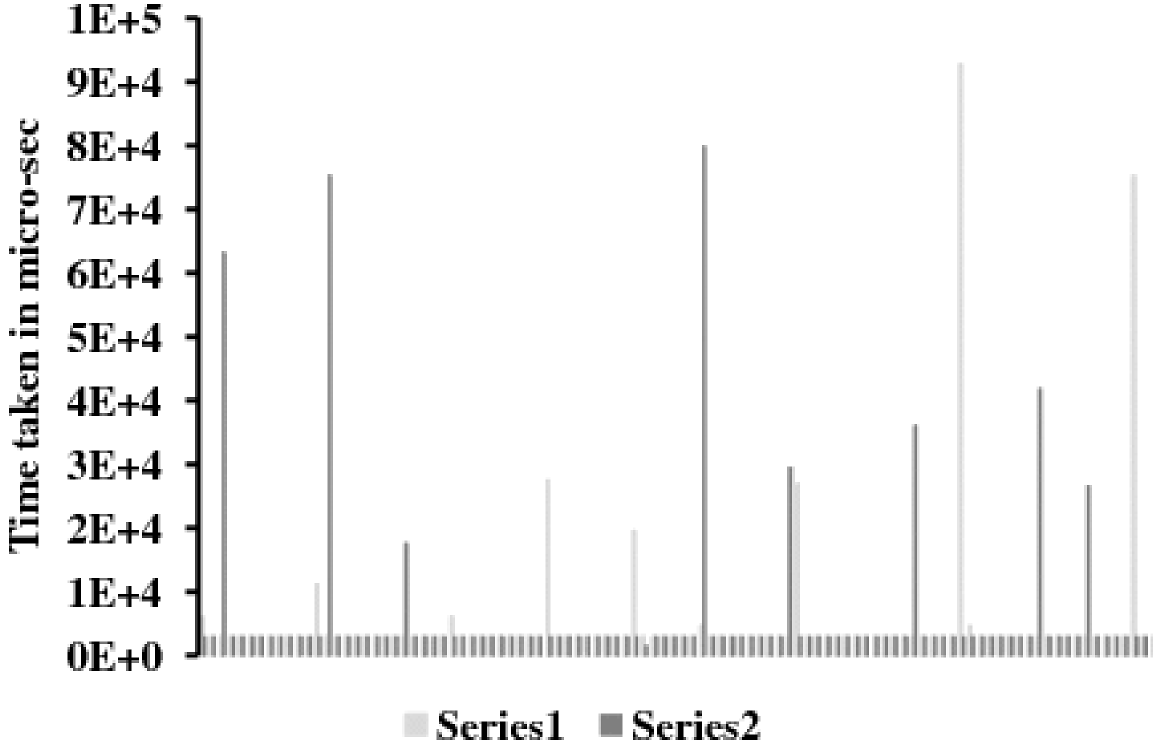

Fig 4.6: Simulation Results of the timing delay. X axis denotes iteration number

Sensitivity Analysis

During the course of the simulation, we have made certain assumptions about the number of nodes, the frequency of occurrence of the Icarus mode, the data transmission time available per node and the duration of the Icarus mode. It must also be noted that we currently do not possess the hardware needed for testing this protocol. Also, the network may be modified before testing. In order to account for these variations, we perform a sensitivity analysis. We continuously vary a parameter and then test its affect by computing the effect such a transformation has on average delay and channel utilization. This is done analytically and the results are then plotted as shown below

Proposed scheme

Parameters

Let,

N_0 : = Number of normal iterations per M_0 Icarus mode iteration

n := Number of nodes

d : = Average distance between node and Base Station

$t_{delay,nor}$:= Average delay in Normal mode

$t_{delay,Ic}$:= Average delay in Icarus mode

$t_{delay,resync}$:= Average delay in resync mode

MATLAB Equations

```
delay_av = (N0*(n0*t_delay_nor+(n0-1)*t_data_nor)+
M0*(t_data_ic+t_delay_ic+t_delay_resync))/(N0+M0)

channel_util = (N0*(n0*t_delay_nor+(n0-1)*t_data_nor)+
M0*(t_data_ic+t_delay_ic+t_delay_resync))./(N0*n0*t_data_nor+
M0*t_data_ic)
```

Default values

Unless stated otherwise

- 5 monitoring nodes
- 1 in 1000 occurrences is an emergency
- Distance between transmitter and receiver = 5m
- Data rate = 1.5 Gbps
- Time spent in Icarus mode on average = 5 minutes

- Time per node for normal mode = 5.5 m sec

Results and Discussion

We ideally would like to see a result which does not result in rapid increases in delay by increasing any one of the individual values. This is because we intend to transmit real time high definition video images using this protocol. We also would like to see an increase in the channel utilization as the values increase as it would represent a greater volume of data exchange between the nodes and the base station, lower protocol overheads and thus imply better observations and hence greater security.

Effect of varying the number of Monitoring nodes

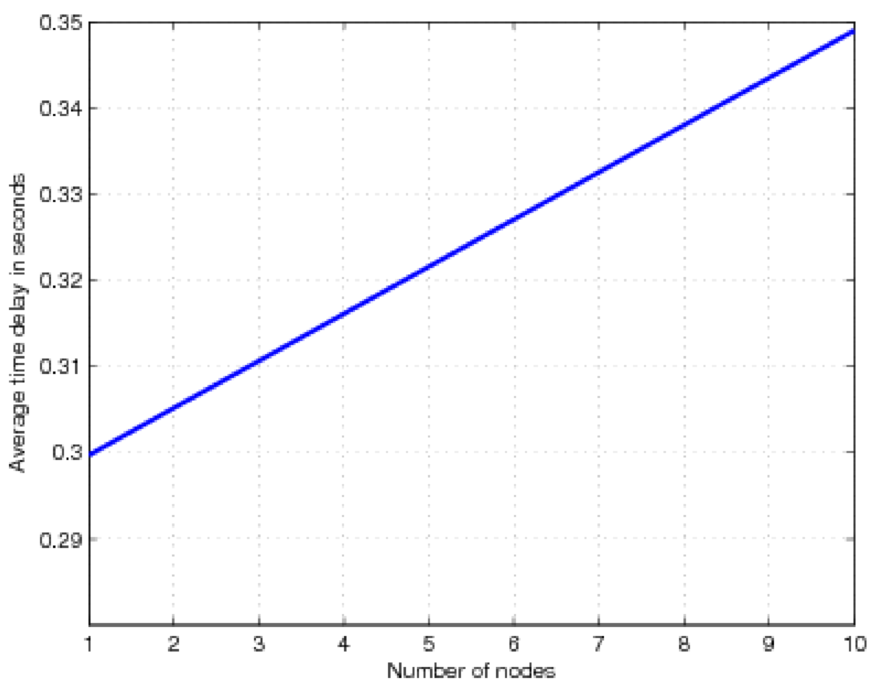

Fig 4.7: Delay vs. Number of Monitoring Nodes

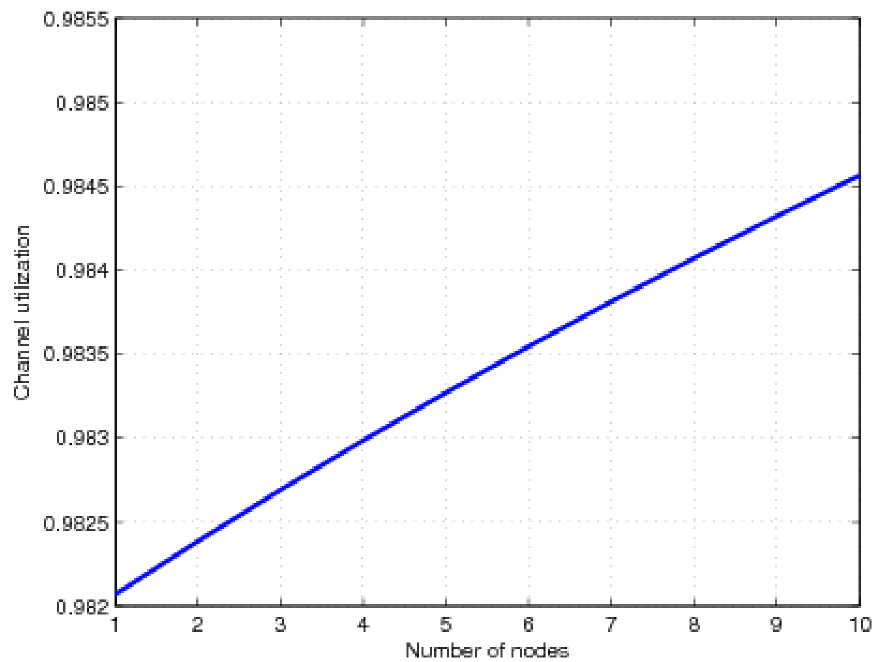

Fig 4.8: Channel Utilization vs. Number of Monitoring Nodes

As shown in Fig 4.7 and 4.8 the delay and channel utilization linearly increase with number of monitoring nodes. However the improvement in channel utilization is negligibly small. However, the delay increases faster. Hence the fewer the nodes per base station, the better. This very small increase indicates that the number of nodes need not be very severely restricted by overall delay requirements

Effect of changing the rate of Icarus mode occurrences

As is evident from Figs 4.9-4.11, there is a significant drop in average delay if one Icarus mode occurs for every 10^3 normal mode occurrences. The drop thereafter is shown on a separate graph so as to clearly illustrate the effect on going from 1 in 10^3 to 1 in 10^6 occurrences. Whilst this might seem a lot each time slot is roughly 5.5 msec. So a 1 in 10^3 occurrence implies an emergency occurring once every 25 to 30 seconds and a 1 in 10^6 implies an emergency occurring once every hour. Hence we can observe events closely even for settings where emergencies are frequent our system can be deployed effectively. Channel Utilization is less important in this regard. This is because the Icarus mode implies that an emergency is being monitored. Hence speed is of utmost essence not optimality

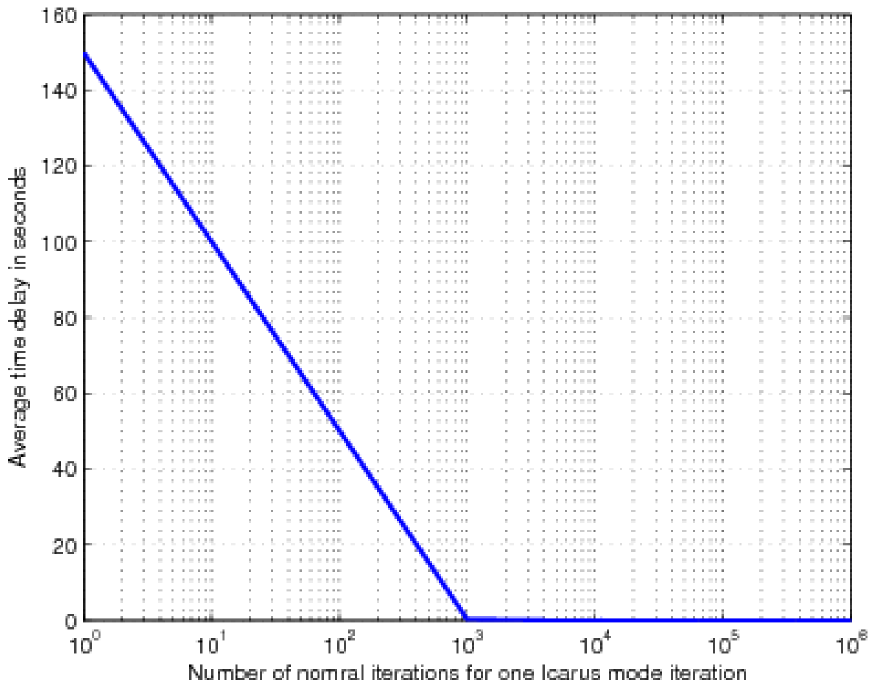

Fig 4.9: Delay vs. Number of Normal mode iterations

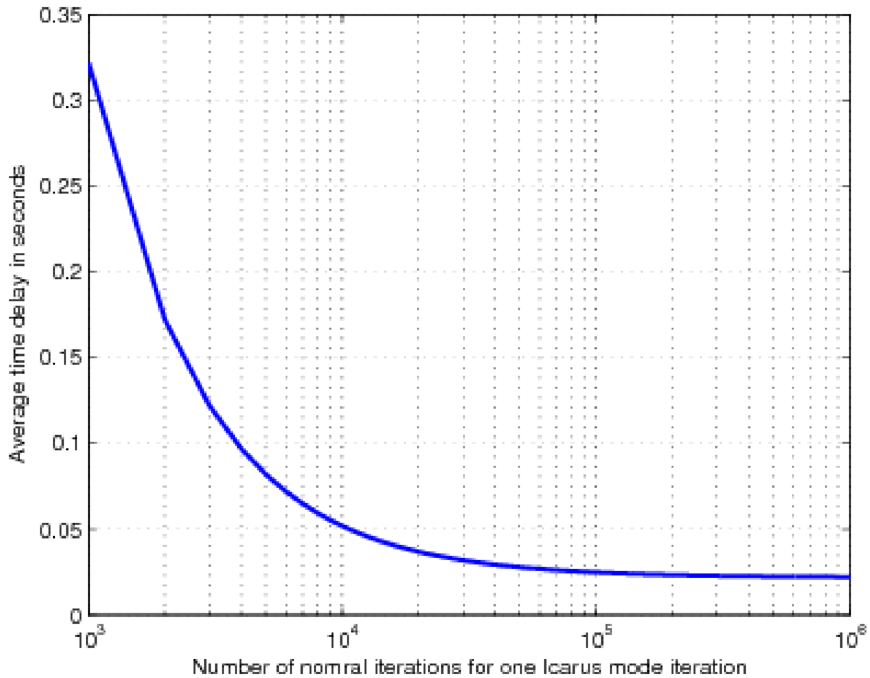

Fig 4.10: Delay vs. Number of Normal mode iterations

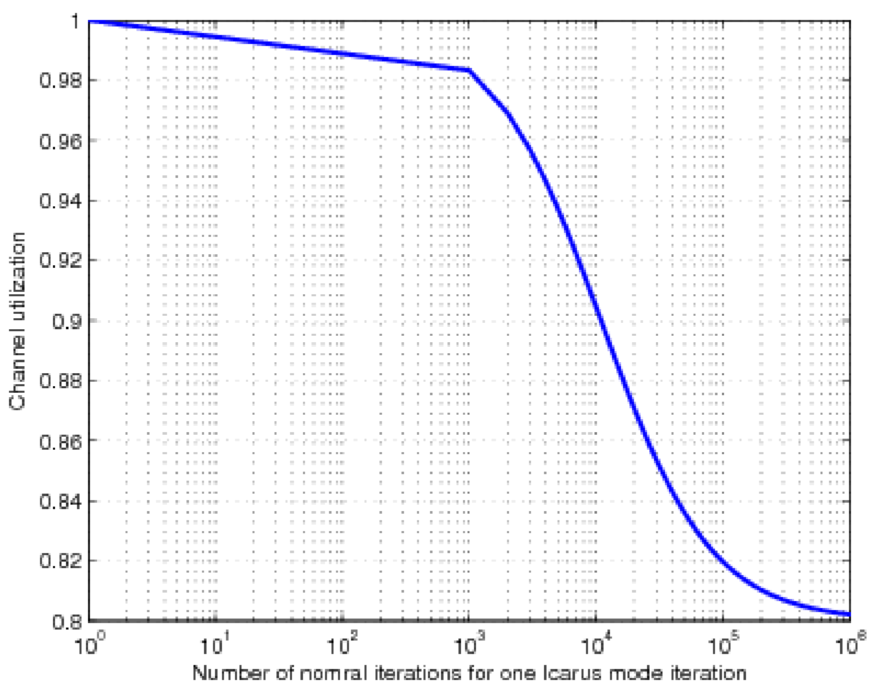

Fig 4.11: Channel Utilization vs. Number of Normal mode iterations

Effect of changing the time given to each node for data transmission

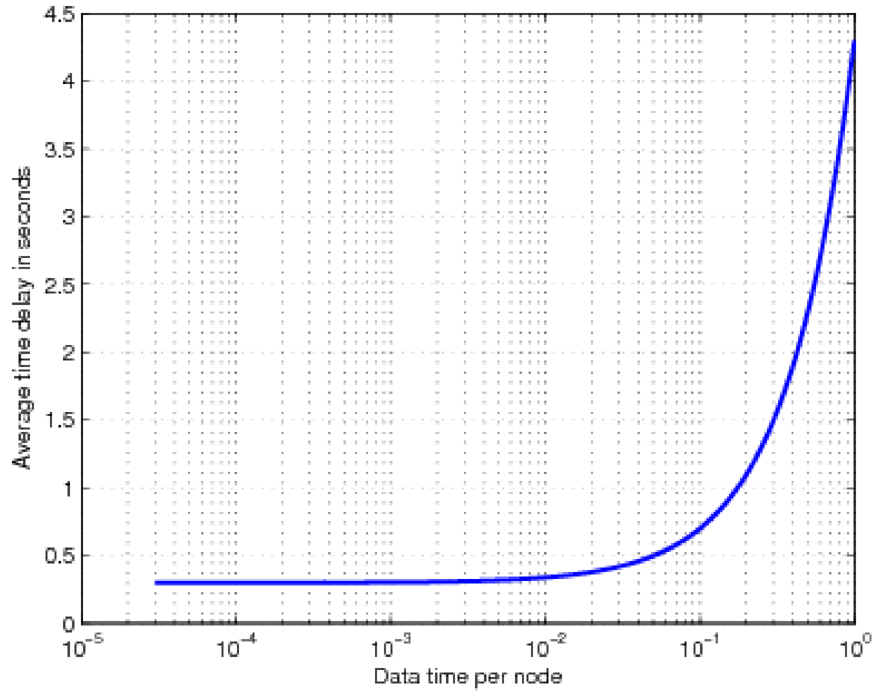

Fig. 4.12: Delay vs. Data Time per node

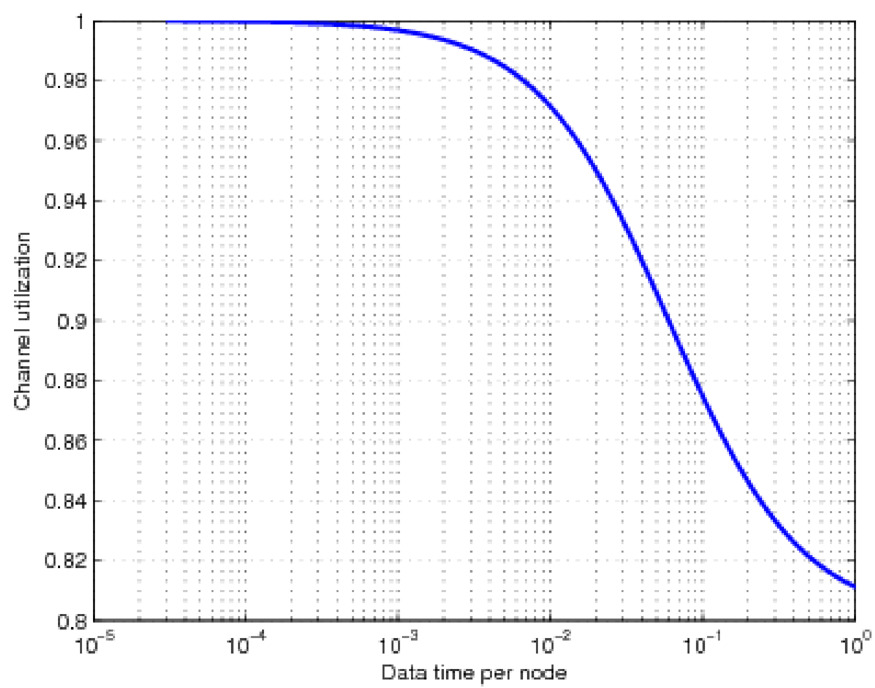

Fig. 4.13: Channel Utilization vs. Data time per node

According to Figures 4.12 and 4.13, average delay remains well under control even if 50-60 msec per node is assigned an average. But should this increase and channel utilization decrease. So it makes more sense to send a few frames at a time rather than large chunks. At 10 msec per data node, the delay is still well below 0.5 sec far faster than the event we would like to monitor. So it is an acceptable value

Effect of varying the duration of the Icarus Mode

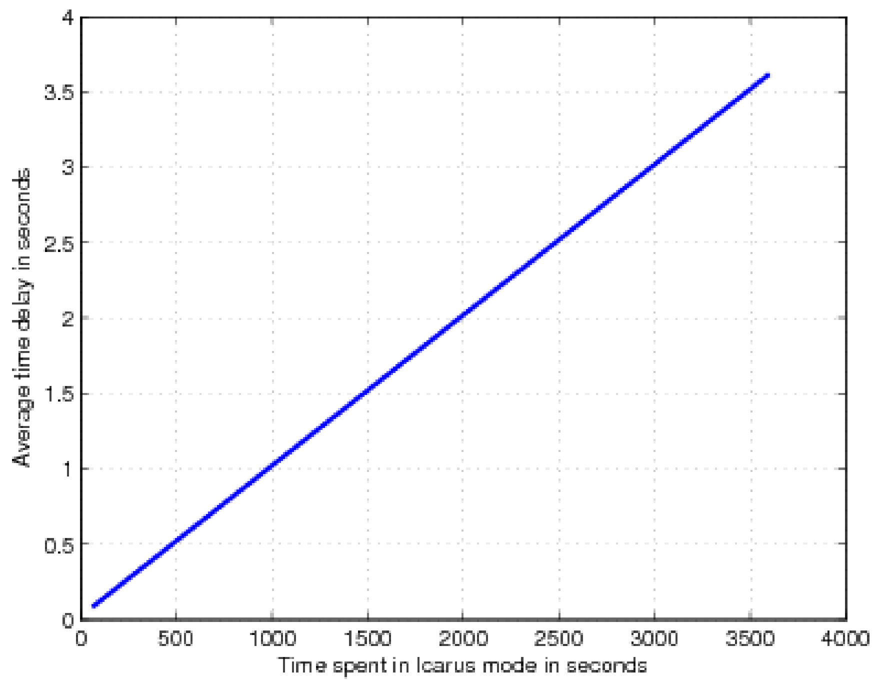

Fig.4.14: Delay vs. Number of Time spent in Icarus mode (linear)

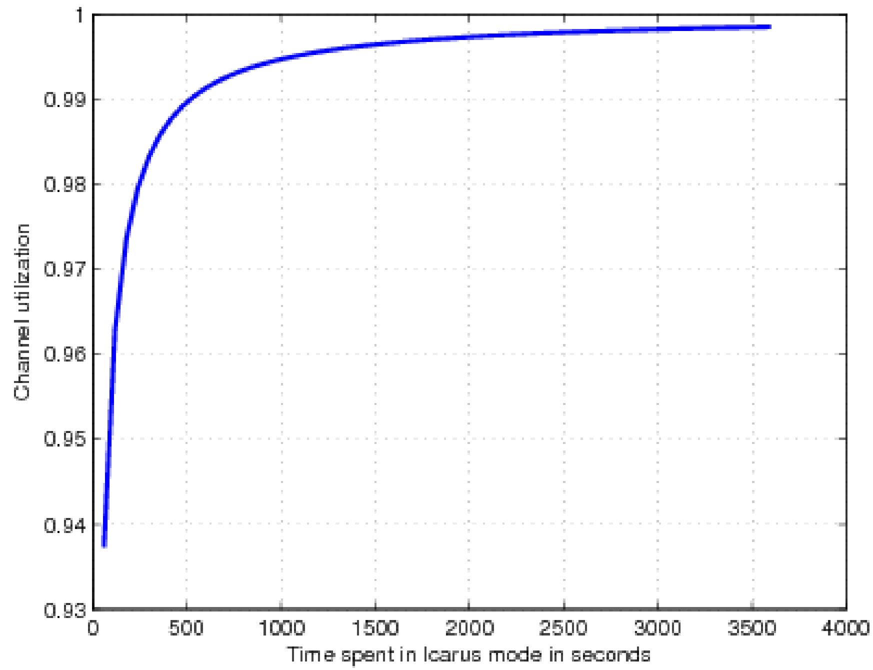

Fig.4.15: Channel Utilization vs. Time spent in Icarus mode (linear)

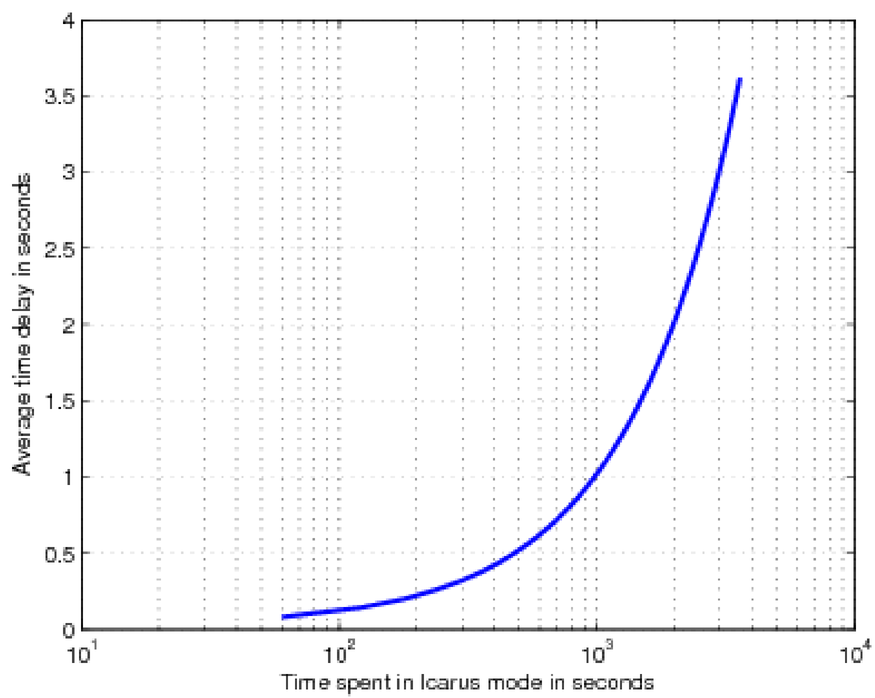

Fig 4.16: Delay vs. Number of Time spent in Icarus mode (log)

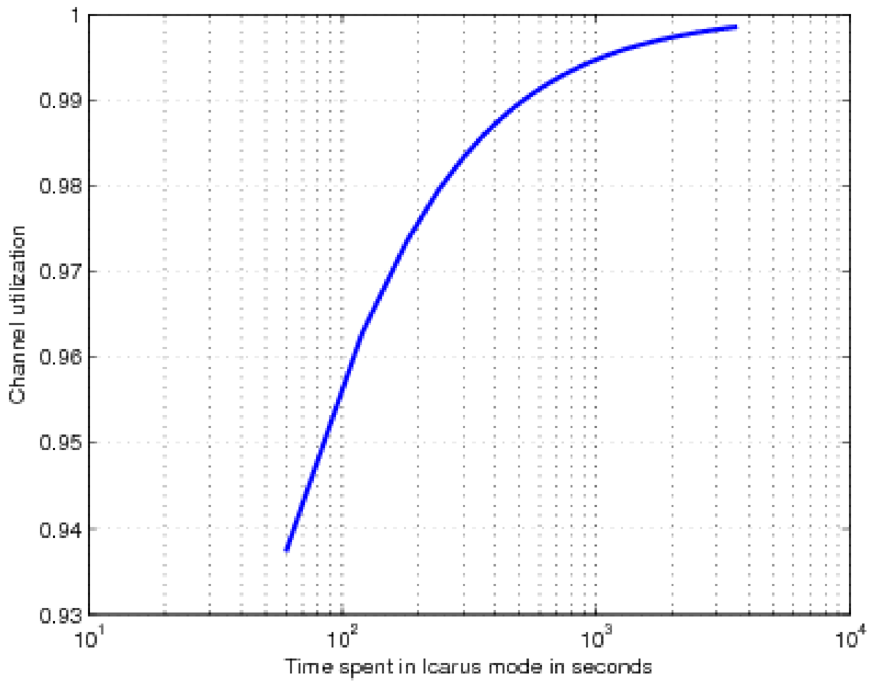

Fig 4.17: Channel Utilization vs. Time spent in Icarus mode (log)

According to Figures 4.14-4.17, increase in channel utilization is not significant as we are measuring the impact of the occurrence of an emergency. Any increase in channel utilization would simply be on account of the additional time devoted to data transmission while the node is in Icarus mode. It is thus not a truly representative Figure. However, delay is a critical parameter should an emergency occur. It is thus critical that the additional delay observed not be very significant. If the emergency were to occur once every thousand normal occurrences and the Icarus mode were to last for one hour, the increase in delay would be negligible. This is consistent with expectations and highly desirable

Summary

We have in this chapter proposed a high bit rate flexible MAC protocol for video and image transmission at 60 GHz. We performed a Monte Carlo simulation and estimated performance. We also studied the effect of variation of parameters on overall protocol behavior. Note however, that throughout we have assumed that there is always a clear line of sight. At 60GHz the beams are exceedingly narrow and prone to blockage from several factors unlike at lower frequencies. Also since we are considering indoor applications, we have to take into account the fact that people will always be moving around. This further complicates matters as it may lead to beam blockage. In the next chapter we shall study the nature of the blockage.

CHAPTER 5

BEAM BLOCKING PROBLEMS

Introduction

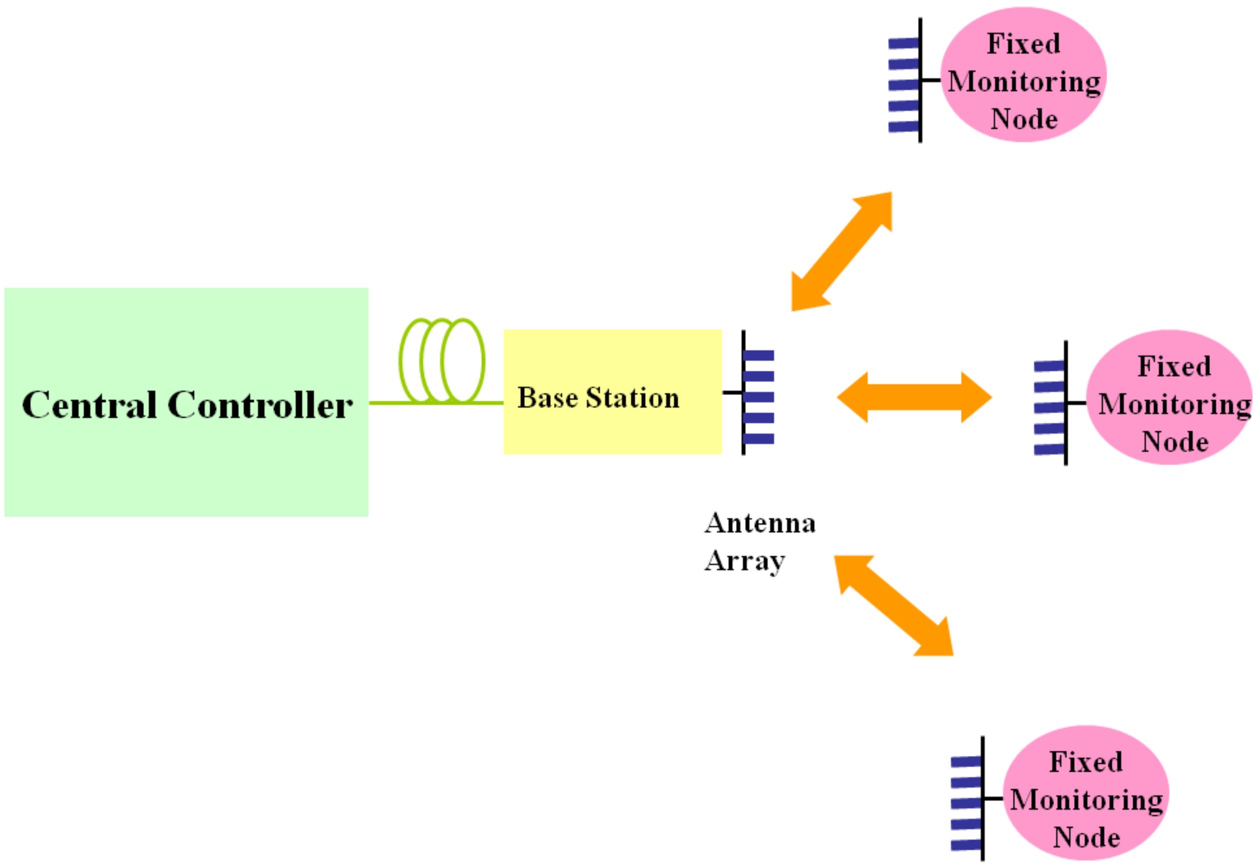

Fig.5.1: Simplified Representation of the network

Consider the representation of a radio over fiber system shown in Fig 5.1 which can be used for sensing/monitoring applications. The following are some of the significant properties of the system:

1. The network is an infrastructure network i.e. nodes and base station are fixed

2. The nodes are assumed to be energy unconstrained

3. The data being transmitted is potentially of critical nature

When deployed with the intent of sensing/monitoring it is inevitable that at some stage the beam gets blocked by a stationary/moving object as can be seen below

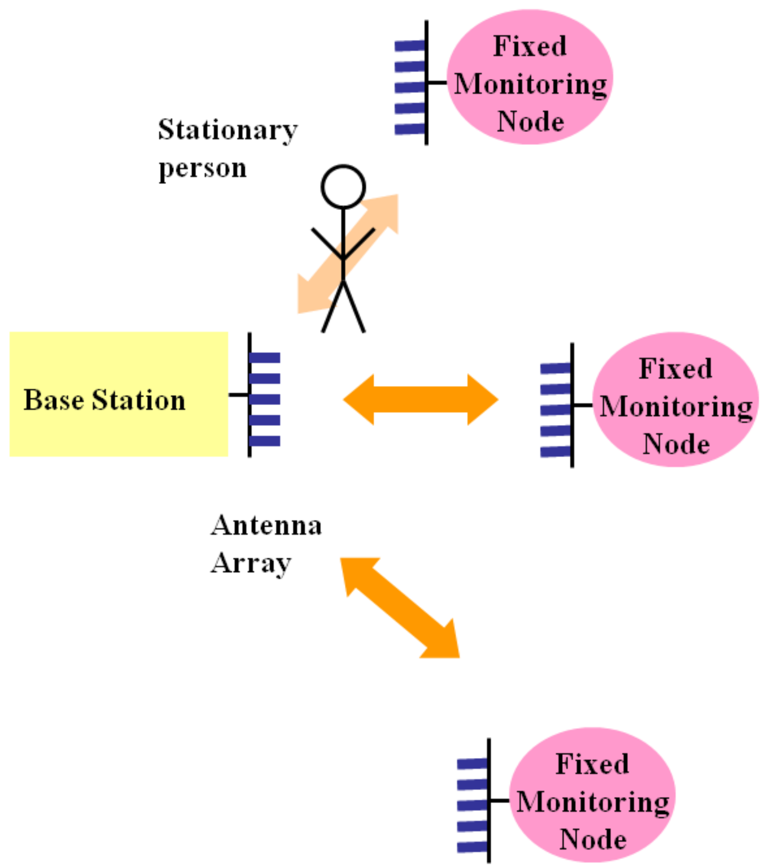

Fig.5.2: The beam between the base station and the monitoring node is blocked by a stationary person in the path of the beam. In this case, no transmission between the node and the base station is possible

In the Figure 5.2 we see one such possible obstruction. In this case, we see what would happen a stationary object was placed in the path of the beam. This is different from what we might call a moving obstruction which is represented in Fig 5.3

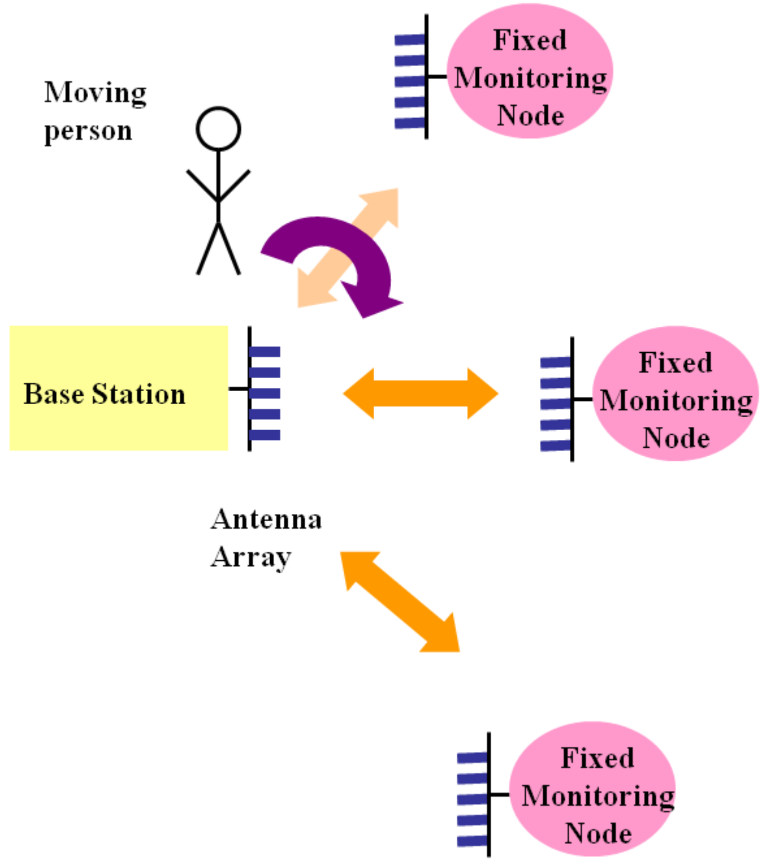

Fig.5.3: The beam between the base station and the monitoring node is blocked by a moving person in the path of the beam. In this case, no transmission between the node and the base station is possible

We shall now attempt to model the loss caused by this blockage. We shall have to estimate the net loss caused on account of the blockage, which implies that we shall have to evaluate loss at any point on account of the Line of Sight transmission and then deduct the blocked beam value from it in order to determine the overall degradation. This technique involves calculating the Line of Sight losses. We shall now proceed to do the same

Assumptions

The question arises how to model the loss in the case of line of sight transmission.

The following are the sources of loss as indicated in Fig 5.4:

1. Inverse Square Law
2. Multipath Fading
3. Noise

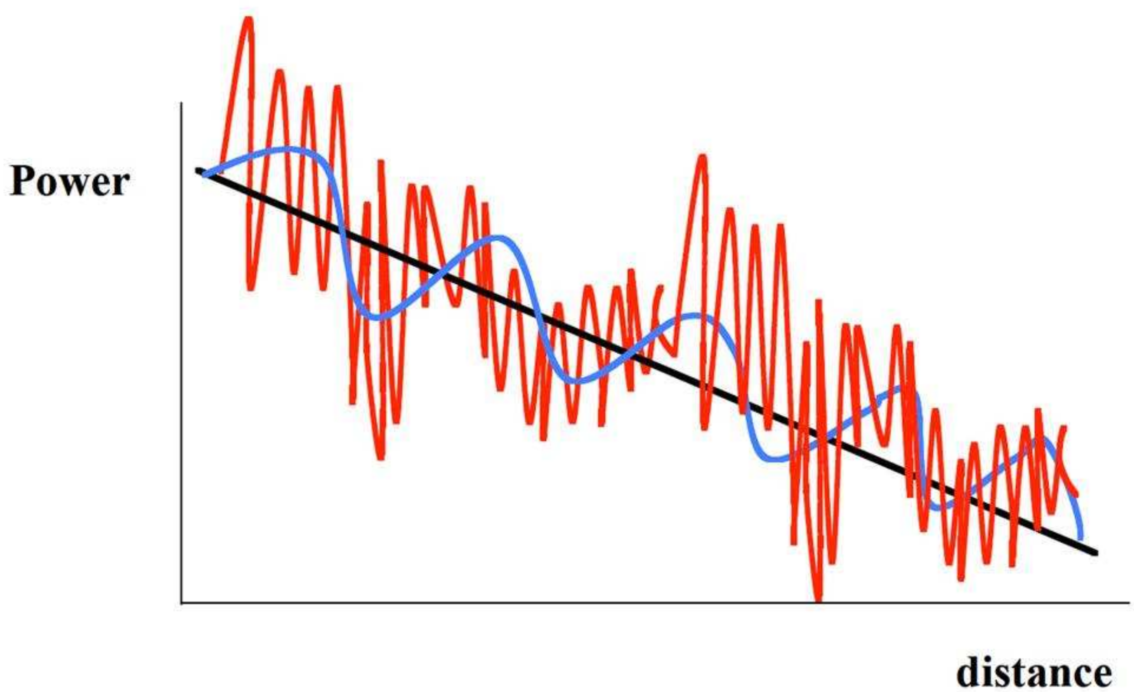

Fig.5.4: Representation of received power as a function of distance

These losses were modeled using MATHEMATICA ® as shown in Fig 5.5 which shows the loss for a transmitter antenna 10m high and a receiver antenna 1.5 m high both with horizontal position, with all three loss sources considered. We can clearly see that the variations on account of the last two factors occur too rapidly to predict and use for MAC protocol design. Also the variation caused by these factors is roughly 10dB peak to trough. Hence we shall for all further models use just the loss due to the Inverse Square law

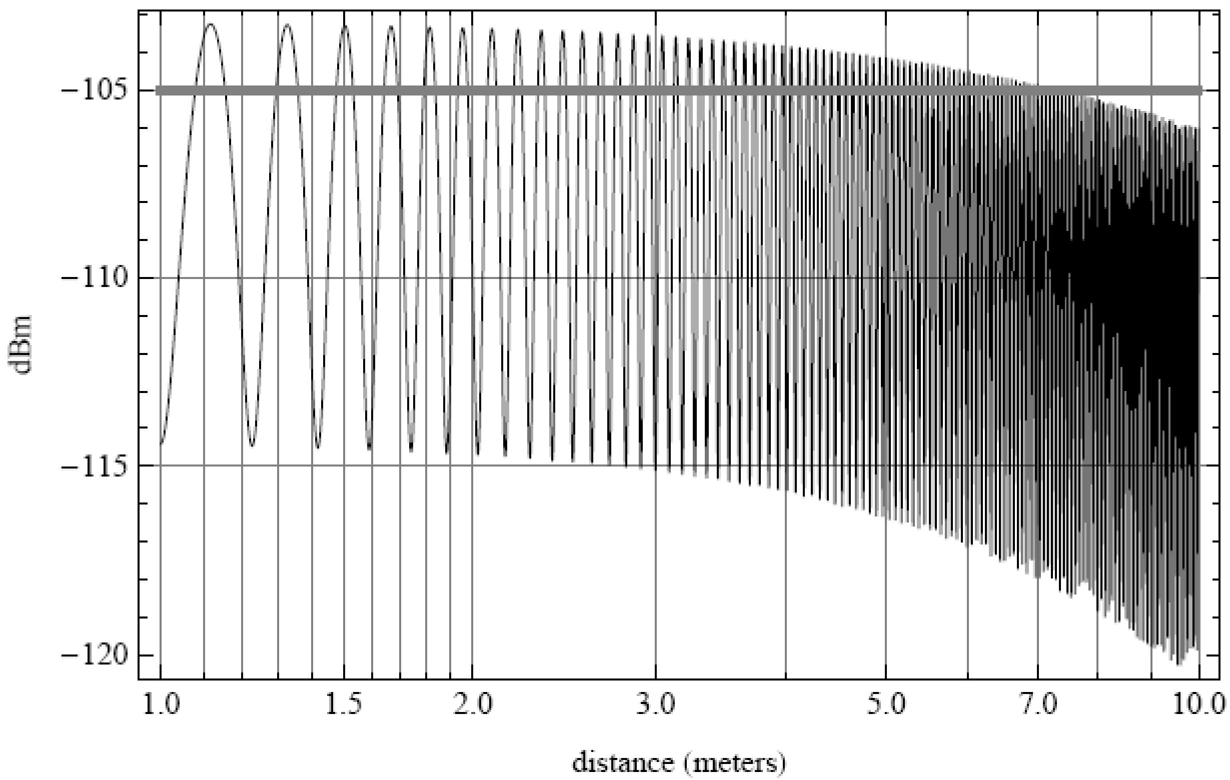

Fig.5.5: Overall loss as a function of distance for Tx antenna of 10m height, Rx antenna of 1.5 m height and horizontal polarization

Another factor that affects the loss is the type of antenna used whether we use an onmidirectional antenna or a directional antenna. This determines the nature of the loss.

Omnidirectional Antennas

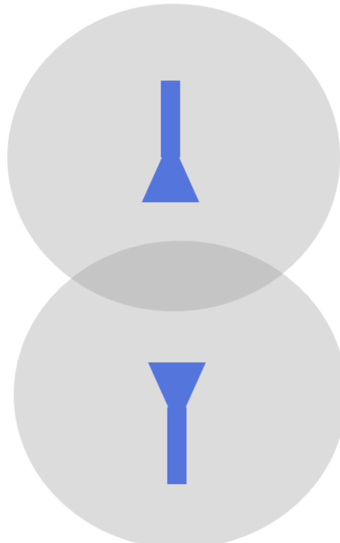

Fig.5.6: Two omnidirectional antennas facing each other

The simplest case is the case of two omnidirectional antennas facing each other as represented in Fig 5.6. This implies that the antenna gains of the transmitter, and the receiver are 1. Stated otherwise, the antenna beamwidths of both antennas are 360 deg. The loss model for the signal from the transmitter to the receiver is assumed to be Inverse Square Model.

The network model is as shown in Fig 5.7. We wish to simulate the effect of beam blockage. Now this factor depends on the dimensions of the blocker, the direction of scattered radiation, the distance of the blocker relative to the transmitter and the receiver. For the purposes of the following discussion we assume that the blocker behaves like a jammer, i.e. it emits a fixed frequency signal identical to the transmitted signal and deducts from it.

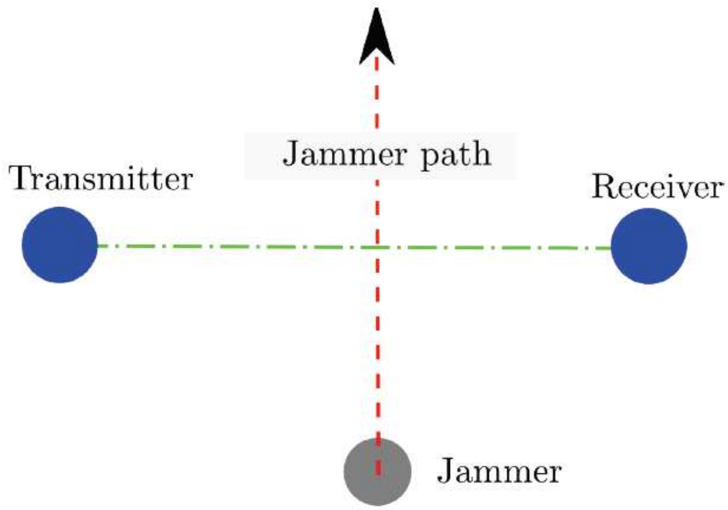

Fig.5.7: Representation of the network being simulated

As the blocker moves from -5 m to 5 m the power received from it gradually increases till it reaches right in the middle of the path joining the transmitter and the receiver as seen in Figure 5.8. The characteristics of the jammer are identical to those of the transmitter. The power loss due to the jammer is the difference between the power received from the two sources. Now, from the Figure 5.8 and 5.9 the peak power loss which is around 8 dB may not appear to be a lot but we must remember that by using omnidirectional antennas we are increasing the power loss during normal operation.

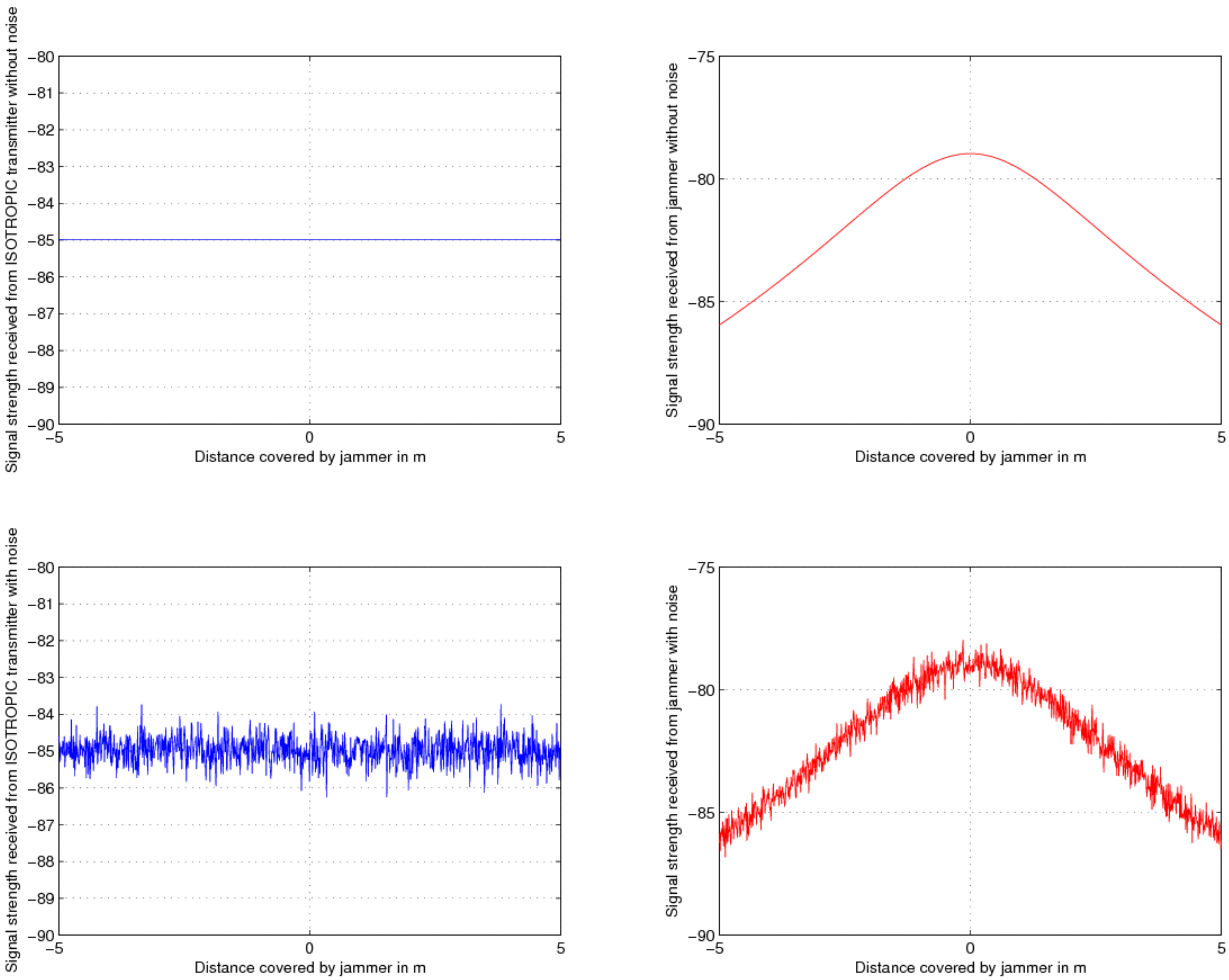

Fig5.8:.Signal Strength vs. Distance covered by jammer in m

The top left represents the power at the receiver due to the Transmitter without noise and in the absence of the jammer

The top right represents the signal strength at the receiver due to the jammer

The bottom two Figures also include the effects of AWGN

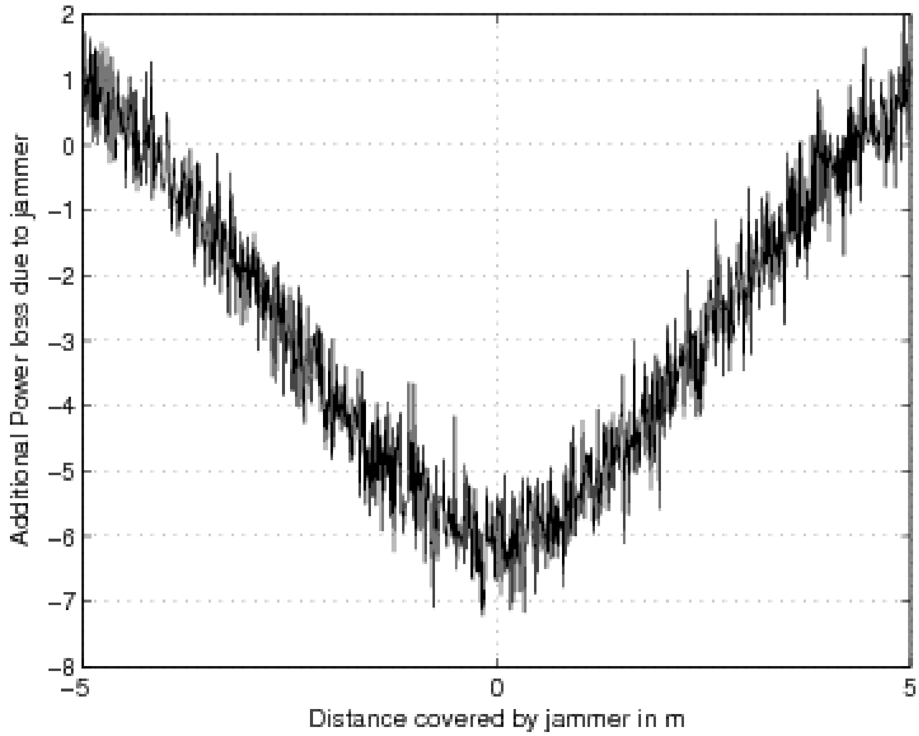

Fig.5.9: Additional power loss due to jammer vs. Distance covered by jammer in m

The two-ray pathloss model is used for the wireless channel and the operation is assumed to be in an outdoor environment at 60 GHz. [26] We shall consider pathloss exponent of 2 and 4 will be used throughout the simulation and actual reception power P_r becomes:

$$P_r \approx (G_t \times G_r \times h_t^2 \times h_r^2 \times P_t)/d^2 \qquad \text{P.E.} = 2$$

$$P_r \approx (G_t \times G_r \times h_t^2 \times h_r^2 \times P_t)/d^4 \qquad \text{P.E.} = 4$$

We use the superscripts d and o to represent the quantity for directional and omnidirectional antenna respectively. For instance, d^d and d^o represent the range within which a certain modulation and coding scheme can be sustained by directional antenna and omnidirectional antenna. Using the equality $P_r^d = P_r^o$, the relation between d^d and d^o can be derived as follows:

$$G_t^d \times G_r^d/(d^d)^2 \approx G_t^o \times G_r^o/(d^o)^2 \qquad \text{P.E.} = 2$$

$$G_t^d \times G_r^d/(d^d)^4 \approx G_t^o \times G_r^o/(d^o)^4 \qquad \text{P.E.} = 4$$

We further assume the reception is not directional (i.e. $G^d_r = G^o_r$) and the directional antenna at the transmitter side has N beams. In addition, the relation between the antenna gain for the directional and the omni transmission can be approximated as follows.

$$G^d_t \approx N \times G^o_t$$

Thus, the range extension factor F_{RE}, which is defined as $d^d{=}d^o$, can be written as

$$F_{RE} = d^d/d^o \approx (N)^{1/2} \qquad \text{P.E.} = 2$$

$$F_{RE} = d^d/d^o \approx (N)^{1/4} \qquad \text{P.E.} = 4$$

The range extension factor FRE for the antenna setting used in the simulation is listed in Table 5.1

P.E.	**Beamwidth (θ)**	**Range Extension Factor (F_{RE})**
2	90^o	2
4	90^o	1.41

Table 5.1: Range Extension due to Beamwidth

Directional Antennas

It was explained in the previous section that the use of directional antennas results in extended range. At 60GHz band, the attenuation due to free space path loss and oxygen absorption is quite severe as we have seen in the second chapter. Thus range is quite severely restricted and is thus very valuable. Thus the use of highly directional antenna beams becomes imperative. The narrower the beam width shall be, the better the performance and longer the range.

We shall now attempt to understand the effects of obstructions on the performance of the same network as seen in the previous section, with the added assumption that both the transmitter and the receiver are assumed to have directional antennas that are perfectly aligned for maximum power transmission. The blocker is taken to have an omnidrectional antenna. The beamwidth of the transmitter and receiver antenna is assumed to be 10 deg. By the calculations in the previous section we can conclude that the range is extended by a factor of 6. Now it is expected that the beam shall remain unblocked for most of the time. When the obstruction moves into the line of sight of the transmitter and receiver, the beam shall be blocked.

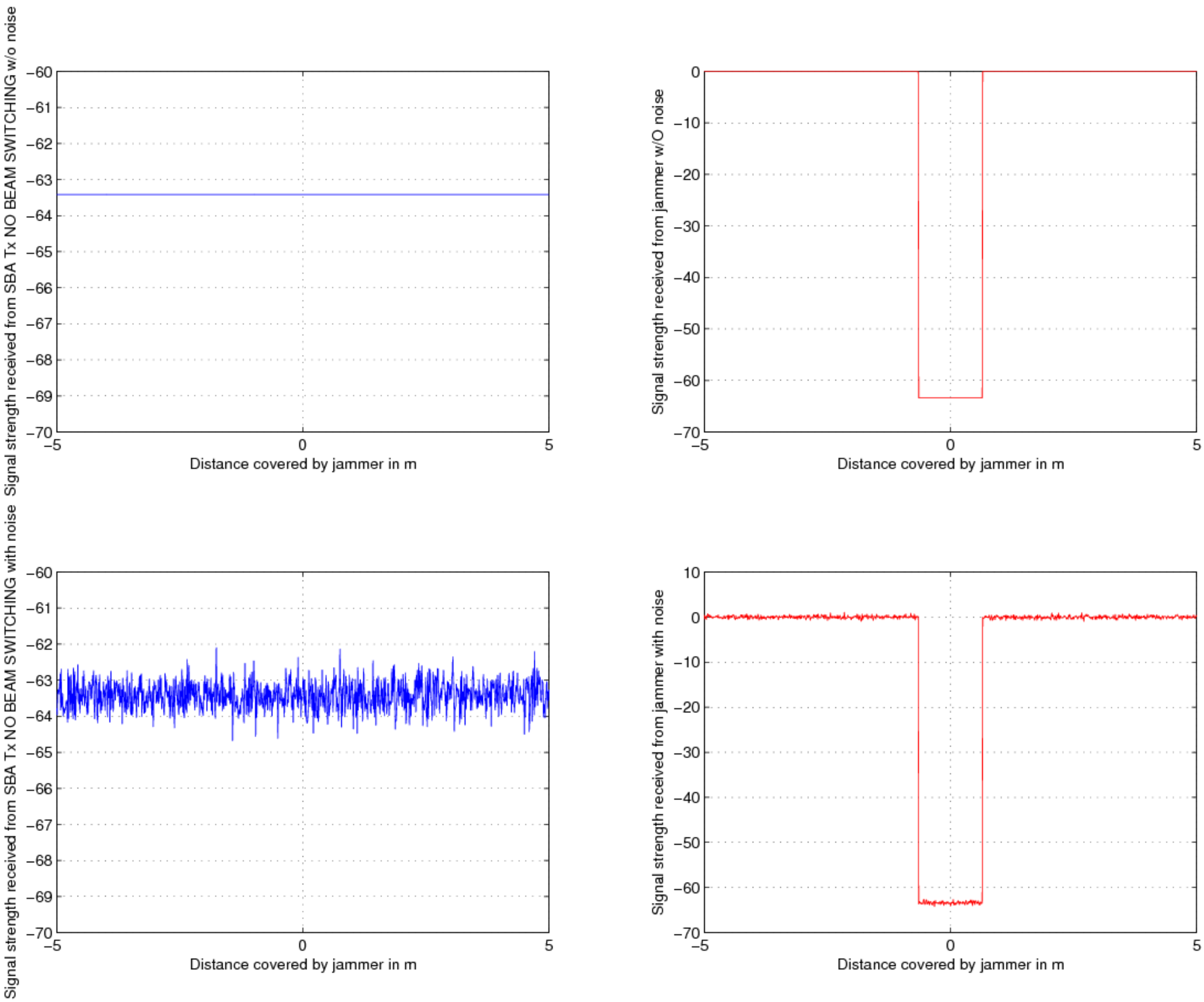

Fig 5.10:.Signal Strength vs. Distance covered by jammer in m

The top left represents the power at the receiver due to the

Transmitter without noise and in the absence of the jammer

The top right represents the signal strength at the receiver due to the jammer

The bottom two Figures also include the effects of AWGN

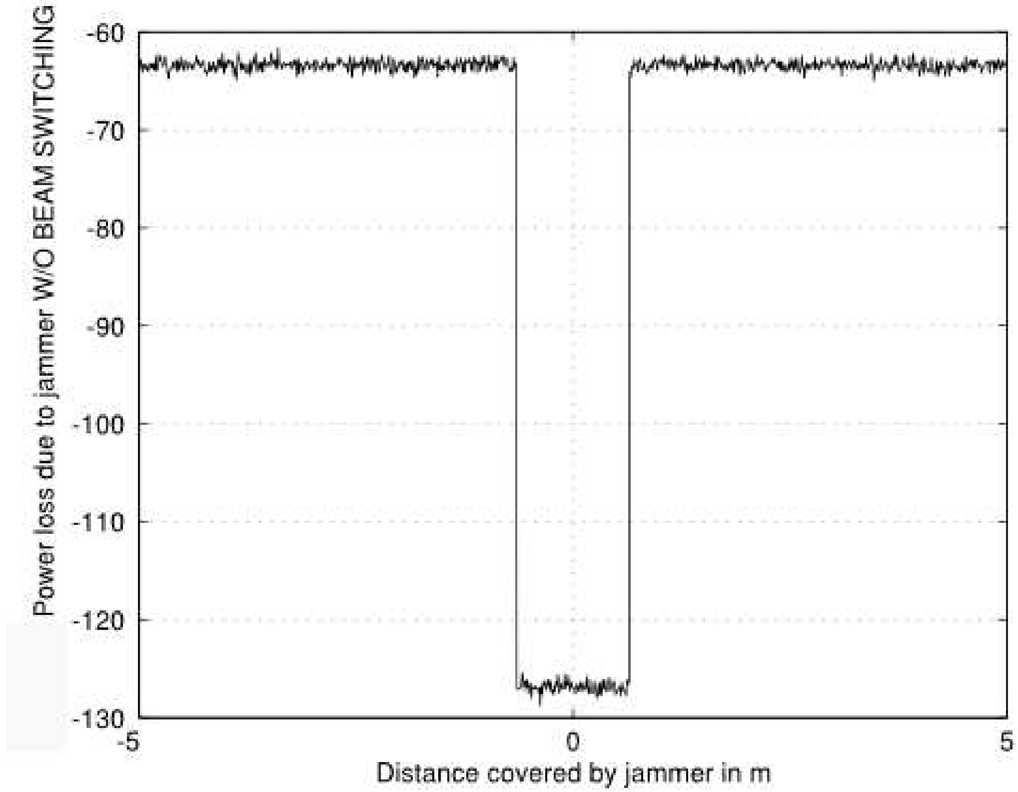

Fig.5.11: Total power loss due to jammer vs. Distance covered by jammer in m

This is exactly what the simulation tells us in Fig 5.10 and 5.11. The conditions that are simulated are the noiseless case and AWGN. The noise for most parts can be neglected. We are assumed that the beams are behaving like rays. The validity of this assumption has been explained previously. We observe that the beam remains unblocked for most of the time, but when the obstruction gets in the way, the power loss is much greater than in the case of omnidirectional antennas. However, the blocking is sustained over much smaller distances and in the case of moving obstructions for much shorter durations.

Moving Beam

Thus if we have to use directional antennas for this purpose we need to switch the direction of the antenna so that the Line-of-Sight is maintained as represented in Fig 5.12. Before we proceed to analyze different beam steering techniques let us first consider the desired set of criteria that the eventual technique will have to possess.

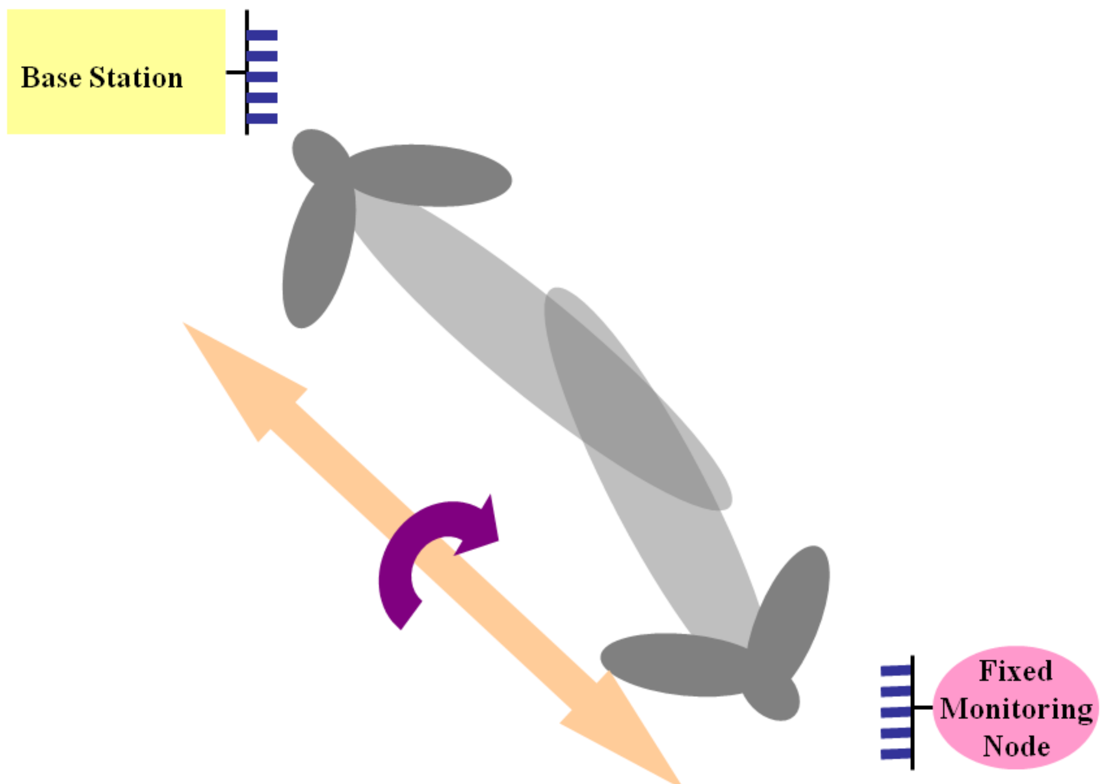

Fig 5.12: Beam Steering in order to maintain Line of Sight

1. Speed: The technique used must be able to locate the node and establish connection in very limited amount of time. It is important to remember that the data that is being transmitted is of video nature and preserving real time nature of data is critical.

However this task can be made easier by utilizing the fact that the network is an infrastructure network

2. Versatility: By this we mean that the beam steering technique should be able to deal with obstructions of varying sizes. Also if the obstruction is very lose to the antenna array; even a small sized obstruction can block the beam. Thus the beam steering technique should be able to steer the beam for a fairly substantial range.

3. Simplicity of Design: While there exist several techniques and several complicated algorithms for beam steering, we must remember that these algorithms require dedicated DSP processors and complicated hardware. These systems are useful if the system has significant interference and fading, the network is ad hoc in nature and the base station has to track the mobile station

Beam Steering techniques

We consider the following three techniques:

1. Use a fixed beam at the Base station/Access point and variable beam at the node
2. Use an adaptive antenna array at the base station and isotropic antennae at the nodes
3. Use switched beam antennas at both base station and nodes

We shall now proceed to examine the benefits and limitations of each technique to determine which is the most suitable to our requirements.

BS:Fixed beam, Node: Moving beam

This applies when the BS antenna has a larger beamwidth than the node antenna. We consider a representative case here. The values are taken fromthe 60GHz mmwave SCBT standard.

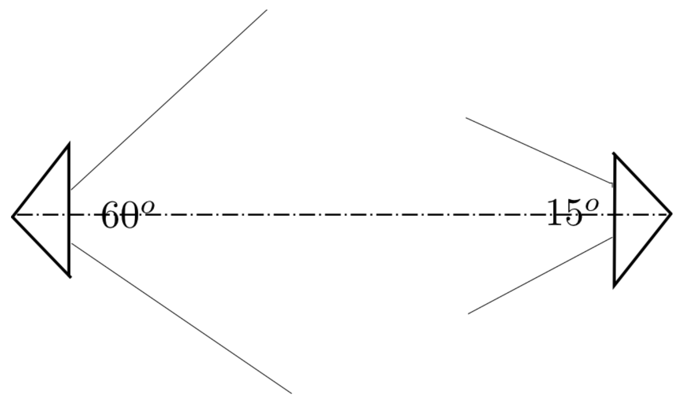

Fig. 5.13: Fixed beam at the base station and moving beam at the monitoring node

As can be seen in Fig 5.13, the node beam can be shifted on either side in case of blockage and establish a path. By simply looking at the diagram some of the limitations become immediately apparent. Firstly, we require that the node shift its antenna. Now there are far greater numbers of nodes than there are base stations. Equipping each with a beam steering antenna and all the auxiliary hardware is expensive. This overkill is particularly apparent when we consider that for significant percentage of the operation time, the node and the BS are able to communicate perfectly well and encounter no obstruction.

Secondly, the extent to which the beam can be steered depends upon the relative ratios of the beamwidths of the BS versus the node. However, it is important to note that we want both antenna beams to be as thin as possible in order to obtain greater range.

However, this system has some very important advantages. If the BS antenna is not kept fixed but is instead moved then the performance of all other nodes in the network can be jeopardized. Also since we are implementing a MAC protocol that uses time division, synchronization between nodes can be destroyed if the base station antenna moves.

Adaptive antenna technology

The adaptive antenna systems approach communication between a node and base station in a different way, in effect adding a dimension of space. By adjusting to an RF environment as it changes (or the spatial origin of signals), adaptive antenna technology can dynamically alter the signal patterns to optimize the performance of the wireless system.

Adaptive arrays utilize sophisticated signal-processing algorithms to continuously distinguish between desired signals, multipath, and interfering signals as well as calculate their directions of arrival. This approach continuously updates it's transmit strategy based on changes in both the desired and interfering signal locations. The ability to track nodes smoothly with main lobes and interferers with nulls ensures that the link budget is constantly maximized.

Since the equipment needed for this sort of operation is expensive and complex, it is advisable to place such equipment in the Base station. This technique can provide Spatial Multiplexing as well.

Thus while this technology may be the most advanced and sophisticated smart antenna technology, some drawbacks exist. Firstly, in order to track the node beam and maintain continuous connectivity, it is required that the node antenna be isotropic. This reduces range, which in the 60 GHz band is already very constrained.

Also, we are implementing a time division MAC algorithm. Continuous tracking makes sense in cellular networks where there is a continuous stream of data to be transmitted from node to base station. In our case the data is in the form of intense bursts. Tracking and steering constantly whilst adapting to the environment implies that this technique is not fast enough.

Thus in conclusion, this technique can be used in ad hoc networks and networks with fast moving mobile nodes but is clearly not needed for our application

Switched Beam Antennas

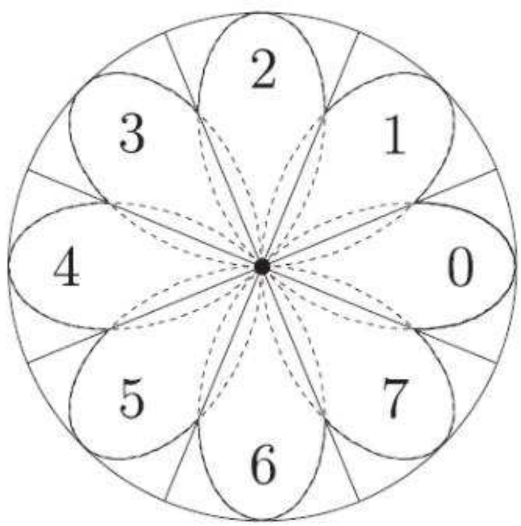

Fig.5.14: Switched Beam Antenna with 8 sectors

Switched beam antenna is another class of smart antenna systems. Contrary to the phased array antennas, there are multiple predefined radiation patterns, as shown in Fig 5.14 & 5.15, and they are simply switched on and off by a switching circuitry called beamforming network (BFN).Switched beam antenna systems from multiple fixed beams with heightened sensitivity in particular directions. [26]

These antenna systems detect signal strength, choose from one of several predetermined, fixed beams, and switch from one beam to another as the path may be blocked by the obstruction.

As depicted schematically in Figure 5.14, this antenna has a directive radiation
8 pattern capable of being scanned to a set (typically a power of 2) of angular directions or beam positions, so that the whole sector is divided in several micro-sectors. Each micro-sector has a pre-defined beam pattern with maximum gain placed in the center of the beam. This beam-switching approach matches perfectly with a time-based system (TDM/TDMA), as the BS antenna is illuminating only in the desired direction in the assigned access instant. [27]

Therefore, the BS cover the service region using a narrow beam synchronized to the sequences of the time assignment. The antenna scanning time, which turns up to be critical for this operation mode can be reduced even to the range of nanoseconds

Also in case of a rather large obstruction, we simply have to switch both beams through a greater number of microsectors. This can be accomplished with great ease and no additional circuitry.

Thus switched beam antennas meet all the three requirements for the beam steering NLOS algorithm.

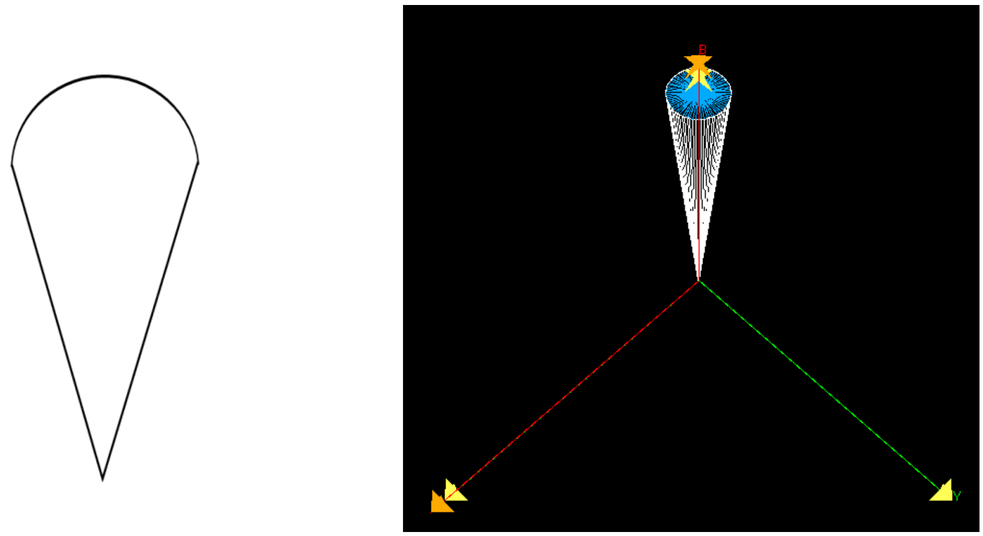

Fig.5.15: Note that the antenna pattern is actually a 3 dimensional pattern. Each sector is actually a cone in 3 dimensions that looks like the Figure on the right

Types of SBA

Switched beam systems can be divided into two groups: single beam and multi-beam directional antennas [27]. In single beam directional antennas, only one beam is active at a given time. Simultaneous transmissions are not allowed because in this system there is only one transceiver. On the other hand, in multi-beam directional antennas, there are several beam patterns and each beam is directed to a different user or a sector. Therefore, simultaneous transmissions are allowed at the same time and frequency.

Factors affecting SBA performance

The results also indicate that the height of the BS antenna has a substantial influence on performance. It has been found that placing the BS antenna can be placed slightly above table height gives a favorable result [28]. This is desirable since table height is in many cases the place where the AP can be readily connected to the fixed backbone network.

Increasing Number of Antenna Elements always has a positive impact on the performance of a system. [28] Thus, from an antenna design point of view, the maximum number of antennas should be limited only by cost constraints and the complexity of the feed and control circuitry necessary to support multiple patches. While the radio channel is the primary source of measurement dispersion due to time varying multipath propagation and channel noise, they can be reduced by a proper choice of antenna polarization. In this application scenario, using Circular Polarization antennas would reduce these parameters with respect to antennas with linear polarization [28]. We shall now attempt to understand the benefits caused by beam switching.

Consider the case of a single transmitter, single receiver with a single jammer. The network configuration is the same as in Fig 5.7. When the beam is blocked the beam is switched. Assuming that the next sectors enable communication, then the power transmitted is less than the maximum. However, there is a significant improvement over the previous case when the beam of the directional antenna got blocked. The improvement is calculated below in Fig 5.16 and 5.17. It is also important to understand the additional benefits of using the switched beam antenna system. Since at any time only one sector shall be switched on, the range during normal operation shall be comparable to that of a normal directional beam case.

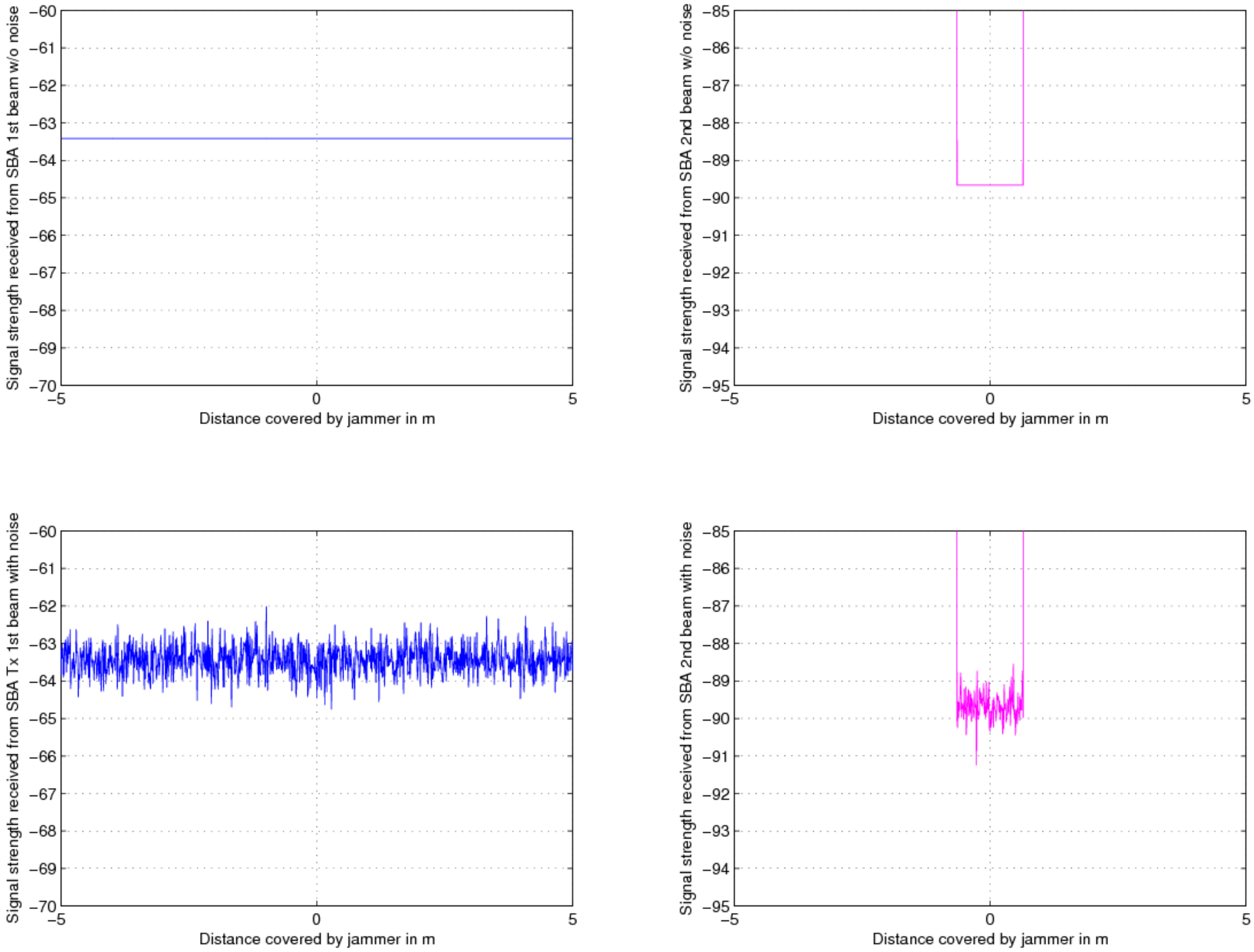

Fig. 5.16: Signal strength as a function of the distance covered by the blocker

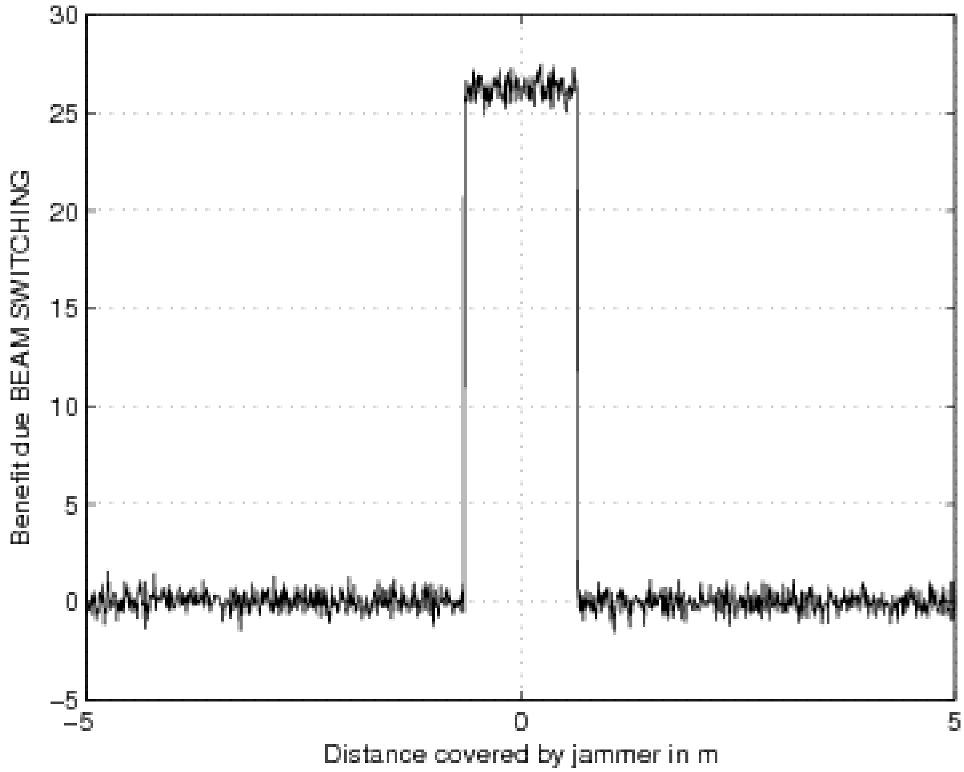

Fig.5.17: Benefit due to Beam switching vs. distance covered by jammer

Beam Selection Methodology

As is evident from the previous sections, if the tranmsitter and the receiver are abel to select the correct sector simulatenously, significant benefits could be derived in the performance of the network. This however, requires that the transmitter and the receiver select the beam appropriately. If the beam is selected inappropraitely, then no transmission is possible. This can be evidenced from Fig 5.18 and Fig. 5.19. In the first case i.e. that of Fig 5.18, communication is possible as the beams are facing each other and overlap shall result in channel formation. In the second case, Fig 5.19 communciation is rendered impossible as they face away from each other and no beam overlap is possible

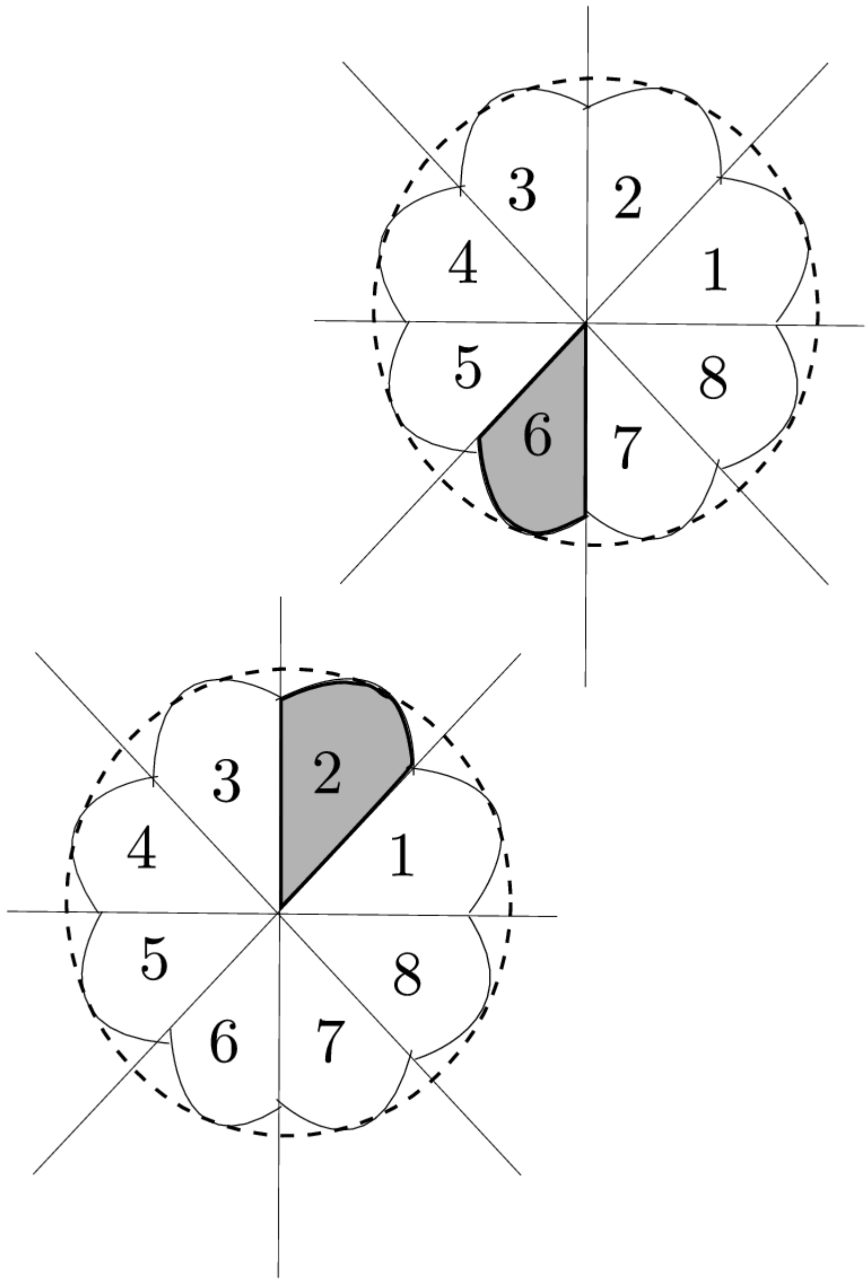

Fig.5.18: The transmitter and receiver select the beam randomly. If the two select a set of beams that are facing each other then it enables communication.

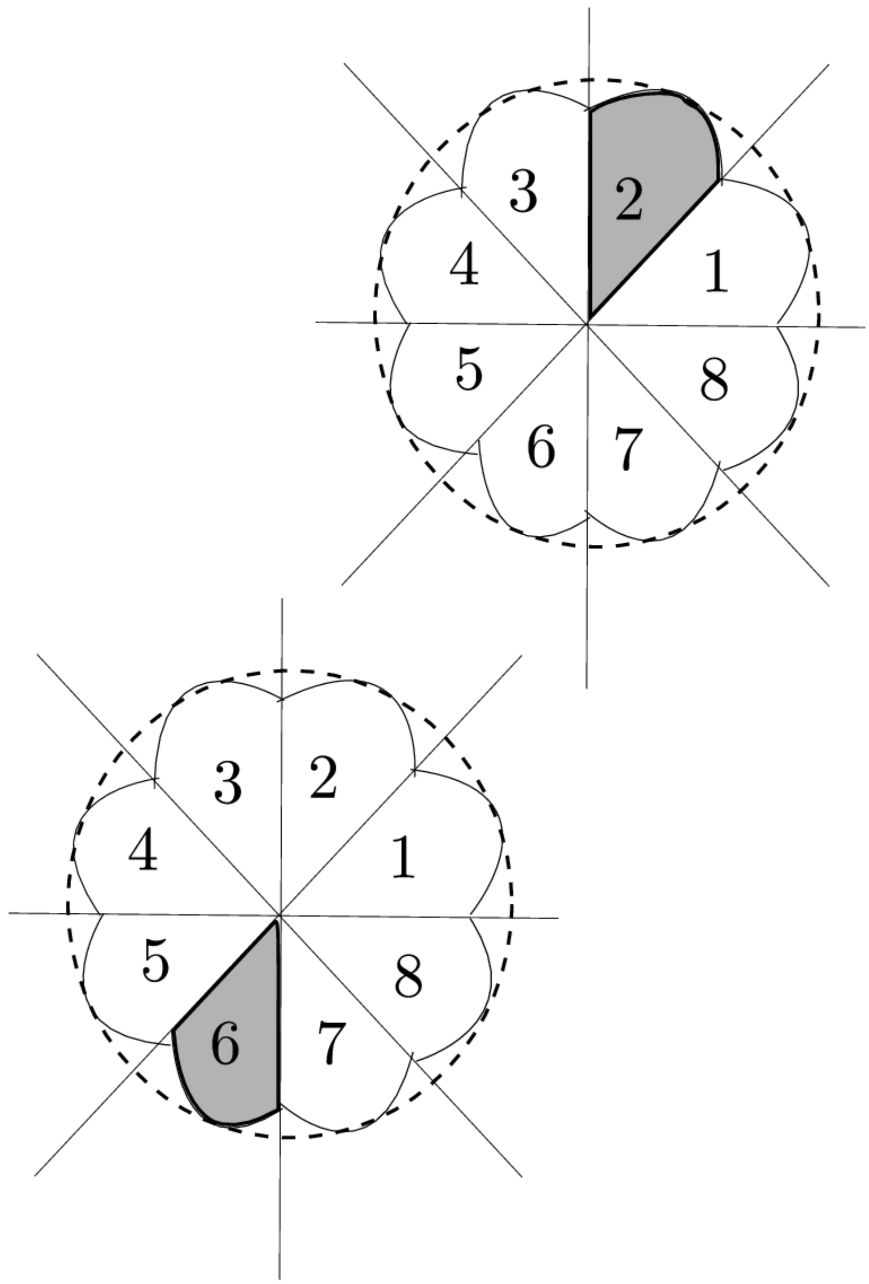

Fig.5.21: The transmitter and receiver select the beam randomly. If the two select a set of beams that do not face each other, then it does not enable communication.

Random Beam Selection techniques

The beamwidth of a directional antenna for either transmissions or reception is fixed and is $2\pi/K$, where K is a system parameter. In other words a node is capable of pointing its antenna in K fixed directions

Node density per unit area = σ

The number of nodes that are within a transmit or receive beam is then $m = \pi r^2 \sigma / K$. We assume that for any node the number of neighbors within the node's transmit or receive beam is fixed and equal to m

In order for a particular node to discover another node in a particular slot its antenna should be pointed towards the other. The probability of this event is 1/K. The converse must also hold true. This implies that the probability of this event is 1/K as well. None of the other $(m - 1)$ nodes that can cause interference to the nodes communication should be transmitting at the same time. Thus,

$$s = \frac{1}{K} \times \frac{1}{K} \times \left(1 - \frac{1}{K}\right)^{m-1}$$

Take the logarithm on both sides and differentiate with respect to K and then equate the result to zero in order to obtain the maximum value of s with respect to K. The maximum value of s occurs when K satisfies the following equation

$$K^2(K-1) = \frac{\pi r^2 \sigma}{2}$$

The results are plotted in Fig 5.20. It can be deduced from the Figure shown below that if the number of nodes is small then the probability of detection and subsequent transmission is nearly unity. However if the number of nodes is large then even after 4 iterations it may not be certain that communication could occur. This necessitates a proper beam selection protocol

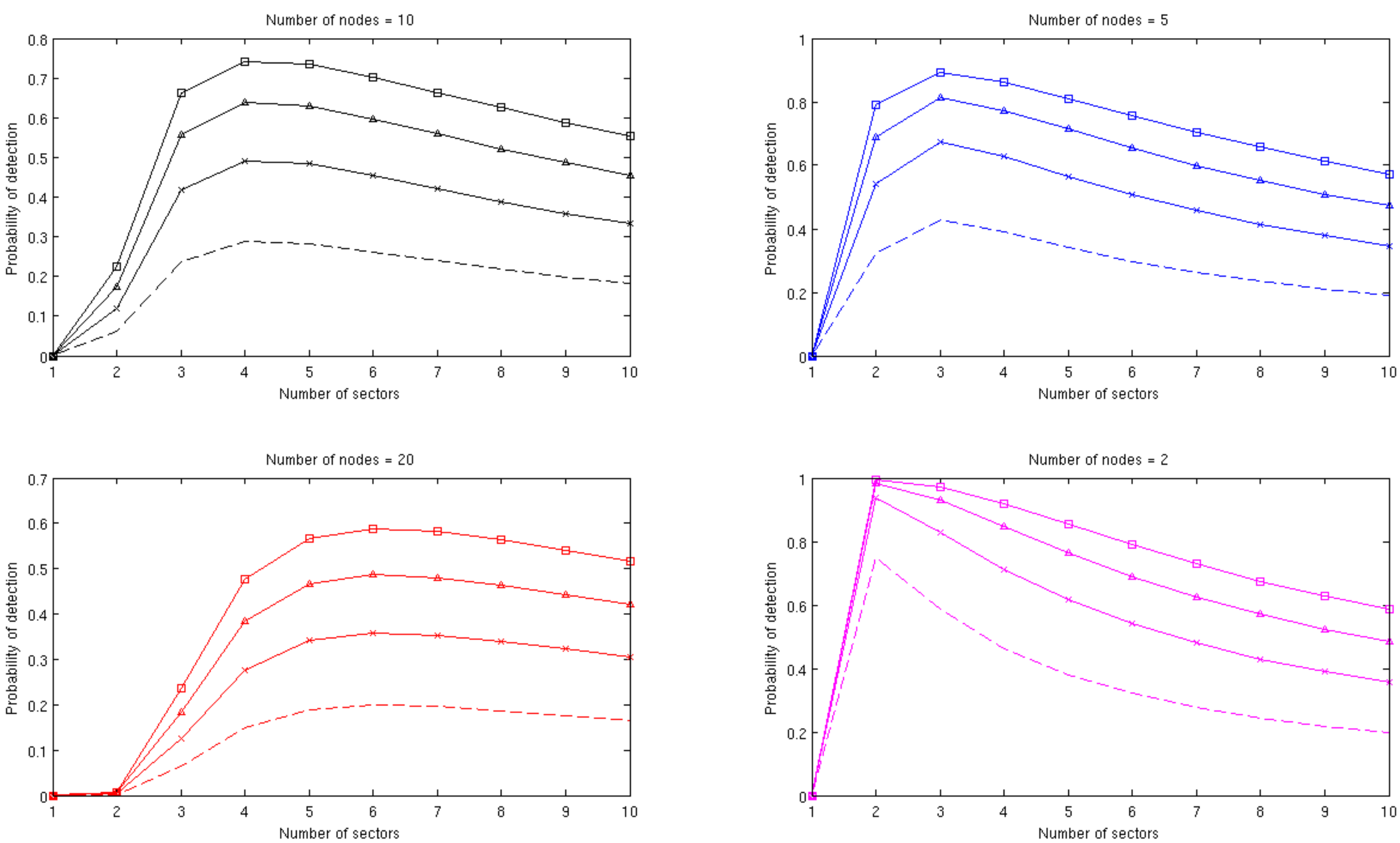

Fig.5.20: Given a random beam selection at the transmitter and the receiver, for a fixed number of nodes, the variation of the probability of detection as a function of (a) Number of sectors and (b) Number of attempts at trying to find a suitable set of beams. In most cases at least four batches of attempts are needed

Summary

In summary, we had designed a MAC protocol that would work for indoor applications. This implied that the beam could be blocked by stationary or moving obstructions. This gives rise to the need to devise a mechanism to continue transmitting even if the beam is blocked. We considered omnidirectional antennas, but discarded the idea after we realized that doing so could severely restrict range. We then proceeded to examine various beam steering mechanisms. Of all of these, Switched beam antennas were found to be the most adequate. We then saw that a random sector selection mechanism does not meet our requirements as the probability of communication taking place is inadequate for our purposed. Thus we need a deterministic way in which we can determine the beam selection. We shall examine this issue and others in the next chapter.

CHAPTER 6

NON-LINE-OF-SIGHT COMMUNICATIONS

Introduction

In the previous chapter we considered the effects of beam blockage on system performance. We considered various solutions to alleviate the problem and we decided that the best possible solution involves the use of switched beam antennas. We also concluded that a random selection of beams for transmission is insufficient as a technique for sustaining communication. We now propose a set of schemes with varying benefits and disadvantages for dealing with this problem.

Single Base Station Case

Protocol Description

This is the first case that we consider. In this we use a single base station, i.e. we do not add any redundancy. This greatly simplifies design and reduces cost but as we shall see, guaranteed end to end communication may not always be guaranteed. We shall now proceed to modify our previous protocol in order to accommodate the possibility of beam blockage. We accomplish this by implementing a handshake exchange before transmission begins as shown in Fig 6.1. The base station sends out node i.d. and timing as usual but instead of beginning transmission as in the previous case, the node sends out an Acknowledge (ACK) signal. If the beam is not blocked as in Fig 6.2 upon receipt of this, the base station shall respond with an ACKREC (Acknowledge Receive). Now if the beam is blocked, as in Fig 6.3, this process cannot take place. This is an effective methodology because the time devoted per node is on the order of a few milliseconds to at most a few seconds. This is far shorter than the time it takes for a human being or any of the usual indoor objects to move into the line of sight and block the beam. Thus if the handshake takes place we can be reasonably assured that the line of sight is not blocked

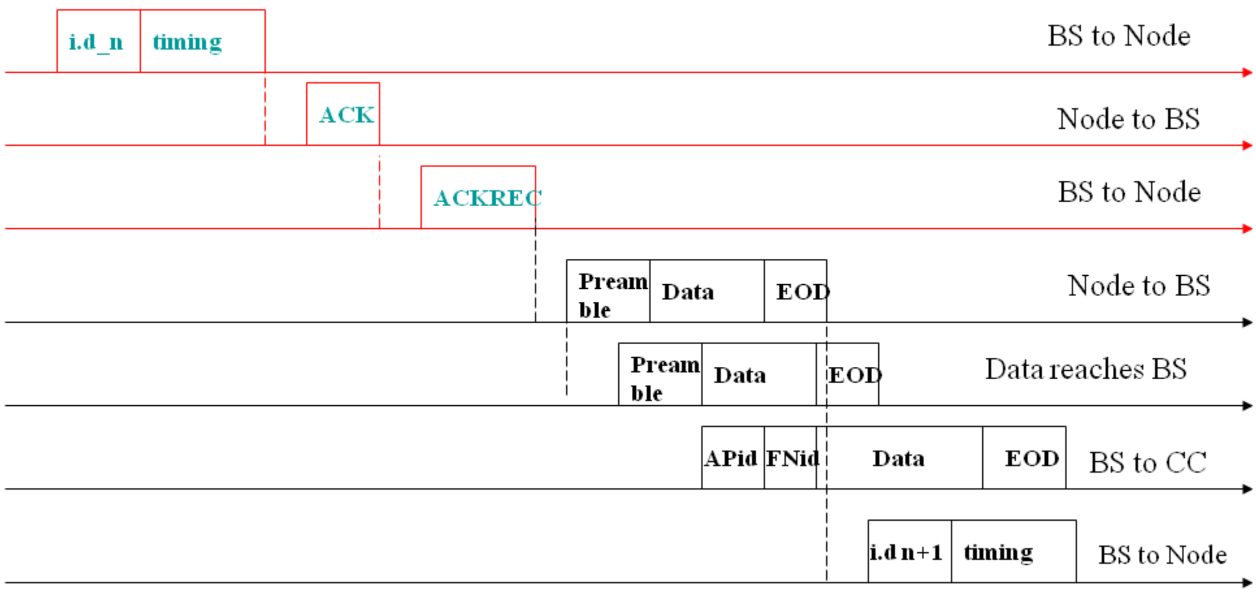

Fig.6.1: Timing diagram with handshake for handling the non line of sight case

Shown above in Fig 6.1 is the timing diagram for steady state operation. A similar modification may be made for the Icarus mode and Resync mode. The rest of the protocol remains the same. Now if the beam is detected as blocked in case of Fig 6.3, we proceed as indicated in the sate machine diagram below. If the base station does not receive the ACK signal, then it knows that it has to switch by one beam as shown in Fig 6.3. Since the base station has not received the ACK signal it shall not transmit the ACKREC signal, hence the node knows that the beam is blocked then it too shall shift the beam by 1.

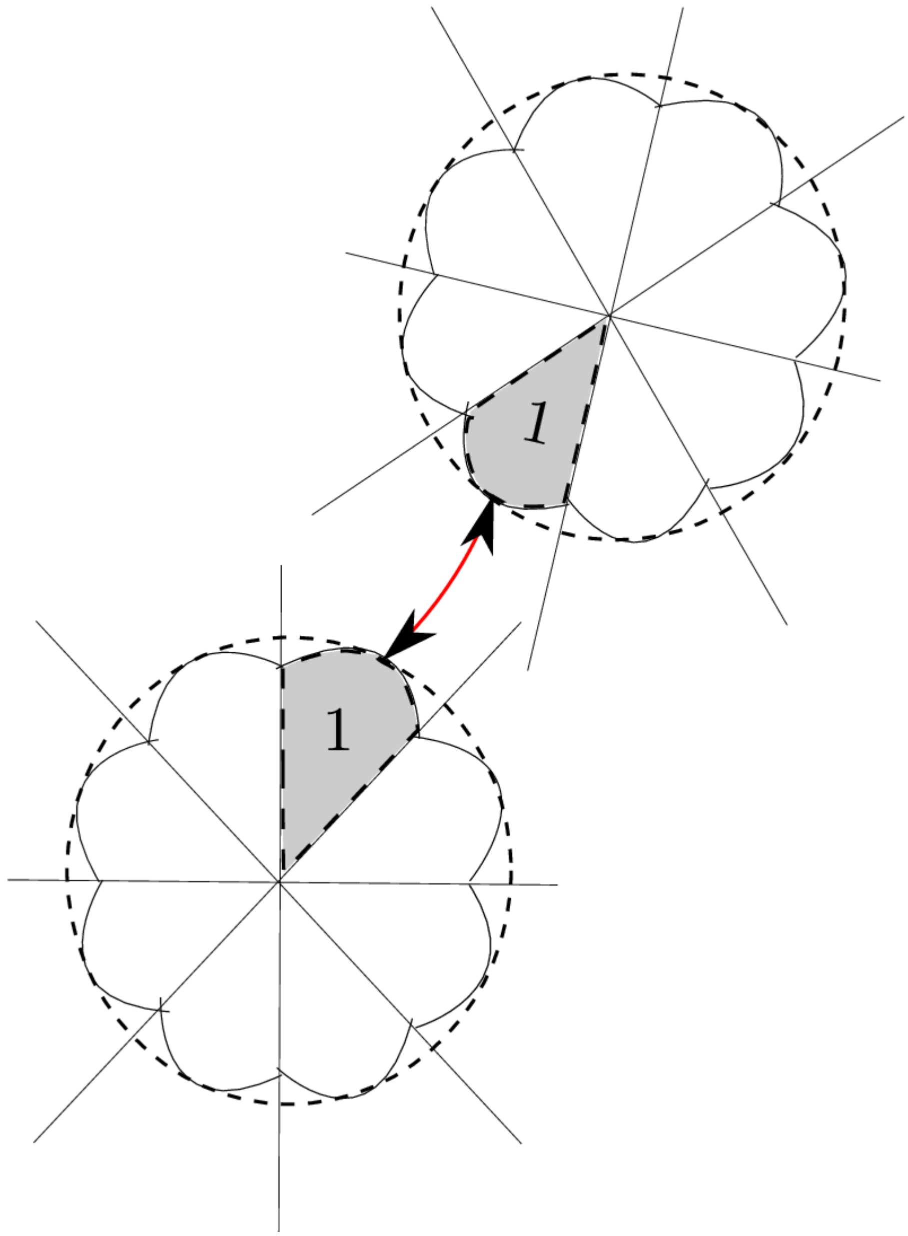

Fig.6.2: Under normal operations beam 1 of the transmitter and the receiver are perfectly aligned and transmission takes place

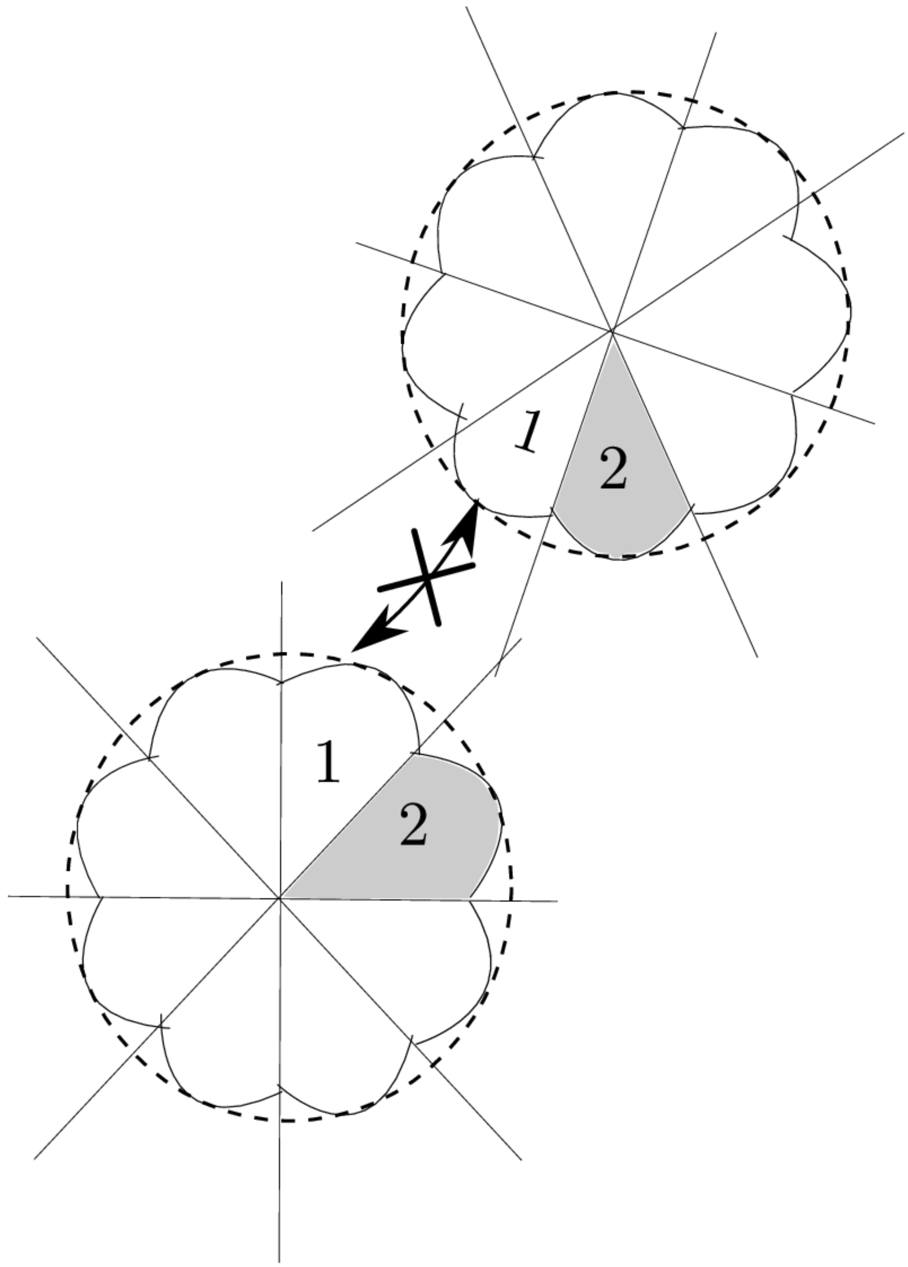

Fig 6.3: When the normal beam is blocked the two beams can switch to a new set and continue transmission if the selection is proper

We now send the i.d. and timing using the second set of beams, if the process takes place as desired then it is acceptable, otherwise we shall repeat the process till we get a set of beams through which communication can proceed.

State Machine Diagram

In addition to the timing diagram, the protocol can be explained in terms of the state machine diagrams in Fig 6.4, 6.5 as well. This method illustrates better the relation between the base station behavior and the node behavior. It also highlights the relationship between protocol behavior and the hardware.

As seen in Fig 6.4 and 6.5 the initial state of both the Base Station and the node is Init during which both of them idle. When the timing data is sent by the Base station, it goes into the 'TimingData' state which corresponds to the Wireless-transmit hardware state. The node is then in the 'RecTimingData' state when it receives the timing data. Its own hardware state is Receive. It then moves to the TxACK mode and if the beam is not blocked, the base station hardware subsequently goes into Wireless-Receive mode and the protocol state of the base station is RecACK. The node then transmits the data which the base station receives until the base station transmits EOD and the node receives it.

If however, the beam is blocked, both the base station and the node switch their beams by one. This behavior is illustrated in Fig 6.4 and 6.5. Tables 6.1 and 6.2 are used to determine the base station and node modes respectively. The states of the protocol correspond to the specific states of the node and the base station.

Base Station

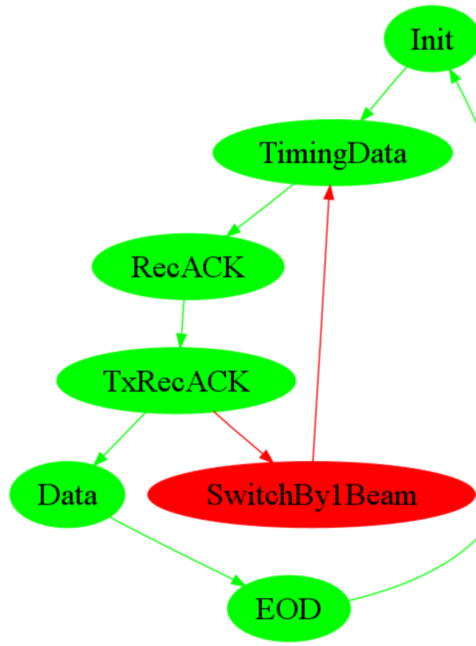

Fig.6.4: State Transition diagram for the Base station

Single BS	
Protocol State	BS State
INIT	idle
TIMINGDATA	WirelessTx
RECACK	wirelessRx
TXRECACK	WirelessTx
DATA	wirelessRx
SWITCHBY1BEAM	wirelessTx+WirelessRX
EOD	wirelessRx

Table 6.1: Description of states of the Base station

Monitoring Node

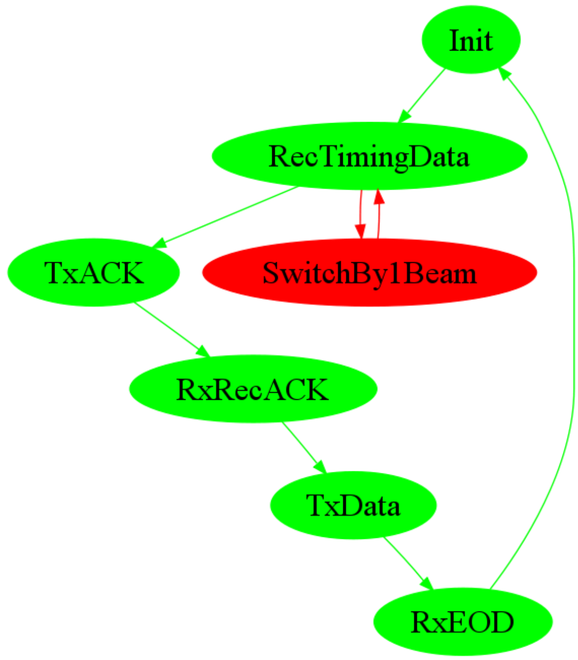

Fig.6.5: State transition diagram for the node

Single BS	
Protocol State	Node State
INIT	idle
RECTIMINGDATA	rx
TXACK	tx
RECACK	trx
TXDATA	tx
SWITCHBY1BEAM	Tx+Rx
TXEOD	tx

Table 6.2: Description of the states of the node

Medium Access Table

				Single BS case									
	Time Slot	BS number	Node no.	BS Beam No.	Node Beam no.		BS Stop				Node Stop		
Original						Beam 1	Beam 2	Beam 3	Beam 4	Beam 1	Beam 2	Beam 3	Beam 4
	1	1	1	1	2	no	yes	yes	yes	yes	no	yes	yes
	2	1	2	2	1	yes	no	yes	yes	no	yes	yes	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	no	yes	yes	yes
After first block													
	1	1	1	1	2	no	yes	yes	yes	yes	no	yes	yes
	2	1	2	4	3	yes	yes	yes	no	yes	yes	no	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	no	yes	yes	yes
New Original													
	1	1	1	1	2	no	yes	yes	yes	yes	no	yes	yes
	2	1	2	4	3	yes	yes	yes	no	yes	yes	no	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	no	yes	yes	yes
After sec. block													
	1	1	1	1	2	no	yes	yes	yes	yes	no	yes	yes
	2	1	2	3	2	yes	yes	no	yes	yes	no	yes	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	no	yes	yes	yes

Table 6.3: Medium Access Table for the single base station case using 4 sector switched beam antenna

Given above in Table 6.3 is the medium access table for a 4 sector switched beam antenna. This table is stored and updated by the Base station. It enables the Base Station to carry out communication reliably. The entries shown above describe the situation that occurs when the primary beam gets blocked. The transmission then continues through the secondary beam. The secondary beam is then assumed to get blocked. The beam is switched again and communication continues. The 2nd node is communicating with the base station using its 2nd beam and the base station is communicating with it using its 2nd beam. When transmission is obstructed, then both of them move over to the next beam and continue with the transmission. It also stores the beams through which to stop transmitting. When transmission is obstructed again, then the beams are switched again. This is reflected in the medium access table.

Simulation

Simulation Parameters

According to [27] the time taken for a SBA to switch beams is given to be of the order of several nanoseconds. Hence we assume the upper limit of 100 nsec. There are two data signals exchanged between the base station and the node separated by 5m. Accounting for the time taken to generate the signals by a factor of two we arrive at the handshake exchange time. This yields the values in Tables 6.4 & 6.5

6 sector Switched Beam Antenna

Protocol # 2a - 6 SBA	
Processing delay 1	100
Sec 1 Data Ex	66.66667
Sum 1	**166.6667**
Processing delay 2	100
Sec 2 Data Ex	66.66667
Sum 2	**333.3333**
Processing delay 3	100
Sec 3 Data Ex	66.66667
Sum 3	**500**

Table 6.4: Simulation parameters for a 6 sector switched beam antenna

8 sector Switched Beam Antenna

Protocol # 2b – 8 SBA	
Processing delay 1	100
Sec 1 Data Ex	66.66667
Sum 1	**166.6667**
Processing delay 2	100
Sec 2 Data Ex	66.66667
Sum 2	**333.3333**
Processing delay 3	100
Sec 3 Data Ex	66.66667
Sum 3	**500**
Processing delay 4	100
Sec 4 Data Ex	66.66667
Sum 4	**666.6667**

Table 6.5: Simulation parameters for an 8 sector switched beam antenna

Assumptions

1. Power received by the Secondary Base Station and the Primary Base Station is identical.

2. All the nodes are at a fixed distance from the Base Stations.

3. Signal is either perfectly received or not received at all i.e. a binary event.

4. The blocking of beam is a purely random event. It occurs once every ten transmissions to one and only one node. This node is chosen at random. The transmission at which the blocking occurs is also randomly chosen.
5. The Secondary Base Station is chosen randomly i.e. coin toss.

Simulation Methodology

Using a random number generator select a number between 1 and 10 to denote the time slot when the blocking shall occur. Now select a number between 1 and 10 so as to denote the node whose beam shall be blocked. Design a coin toss simulator to determine which node shall be blocked. Take 1000 iterations and then take the average. This gives us one data point. We perform this 20 times. We then repeat the experiment if the blockage were to occur once every 20 transmissions and once every 50 transmissions.

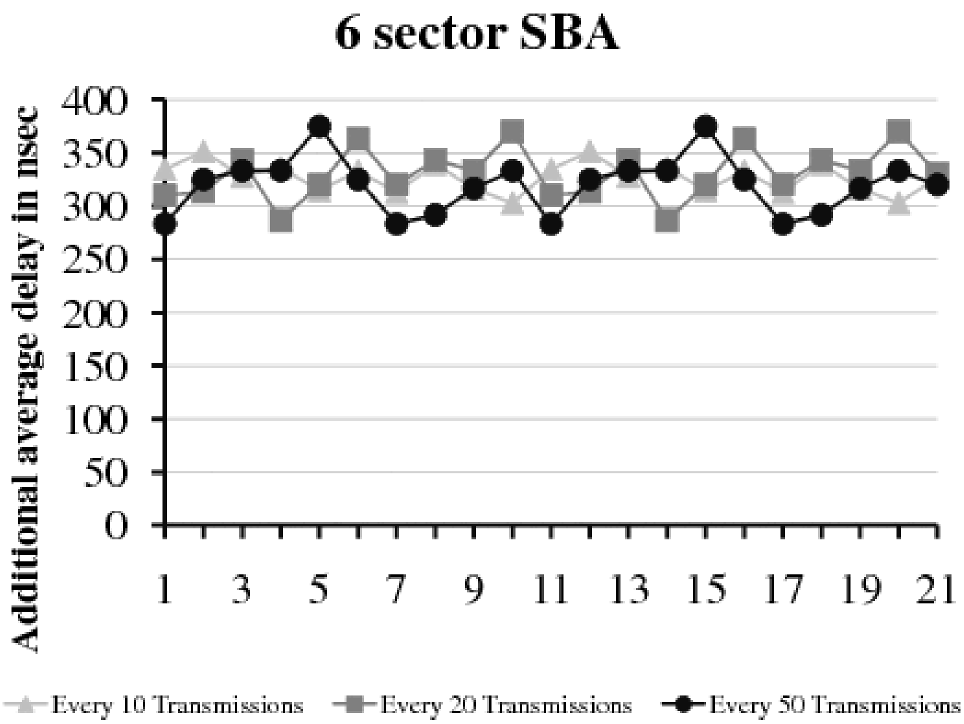

Fig.6.6: Additional average delay. The x axis contains the iteration number

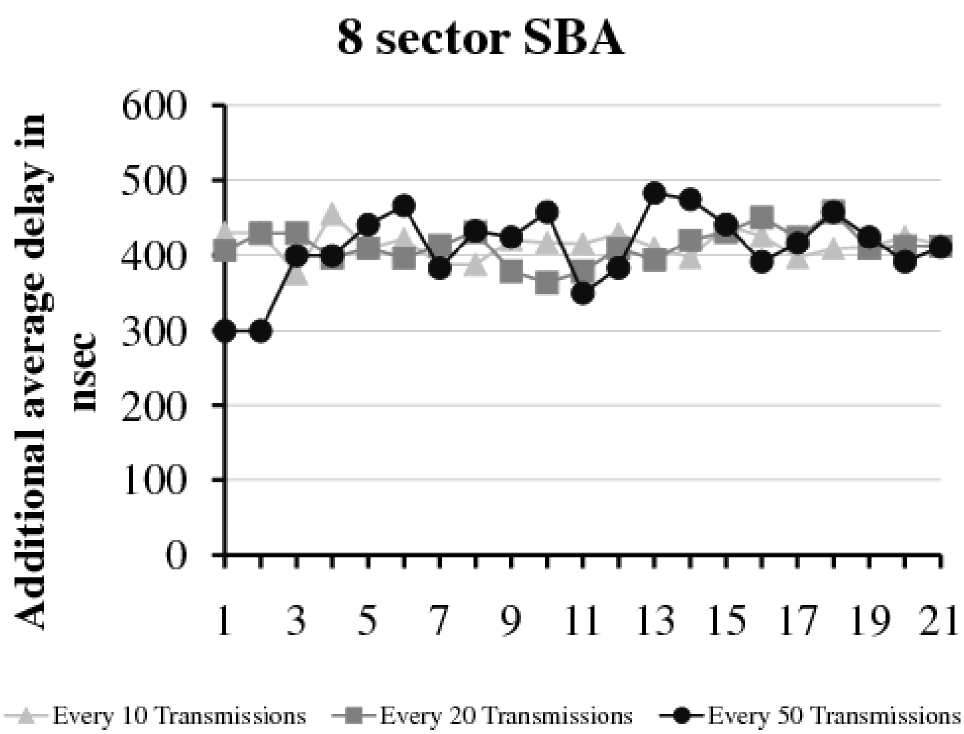

Fig.6.7: Additional average delay. The x axis contains the iteration number

The results in Fig 6.6 and 6.7 indicate that the delay varies from iteration to iteration. The average additional delay depends upon the number of times the 1st, 2nd or 3rd beam from the primary beam is selected. There does not appear to be a strong dependence upon the number of times the beam is blocked. The values in case of a 6 sector switched beam antenna varies from 250 to 400 nsec while those for an 8 sector switched beam antenna vary between 300 to 500 nsec. Overall the performance of the 6 sector switched beam antenna appears to be marginally better. However, the beamwidth of each sector in the case of a six sector antenna is wider. This implies that the range of this antenna is lower, range varying inversely to antenna beamwidth as shown in chapter 5. Also it implies that such an antenna can accommodate fewer nodes, so, this might not be entirely advantageous. Since the additional delay does not appear to be very significantly different, it might be preferable to select an antenna with greater number of sectors.

3 Base Station Case

Protocol Description

Consider the network shown in Fig 5.5 that consists of a central controller, a base station and some sensor nodes. Since we are envisaging the application of such a network for monitoring applications in an indoor environment, we must take into account beam blockages caused by humans or by placement of objects in the path of the beam between transmitter and the receiver. Several different schemes are possible in order to alleviate this condition. One such scheme using a single base station was outlined by us earlier. We now turn our attention to the case when more than one base station is used. The benefit of this scheme is to guarantee end to end delivery even in the case of a block, irrespective of the size of the primary beam blockage.

In this scheme three base stations are placed along the vertices of an equilateral triangle surrounding the monitoring nodes (Ref Fig 6.8). The three base stations are connected to a fiber backbone that is also connected to the central controller. The three base stations exchange data by using this backbone. This particular placement is chosen as this way we can ensure that the maximum received power is the same in the case of the primary and two secondary receivers if we are using a six beam switched beam antenna. If we are using a 4 beam or an 8 beam antenna, placing the base stations on the vertices of a square is recommended. Now consider the case when the primary beam is blocked. This blockage is discovered by means of the ACK and ACK-REC mechanism described by us in the previous section.

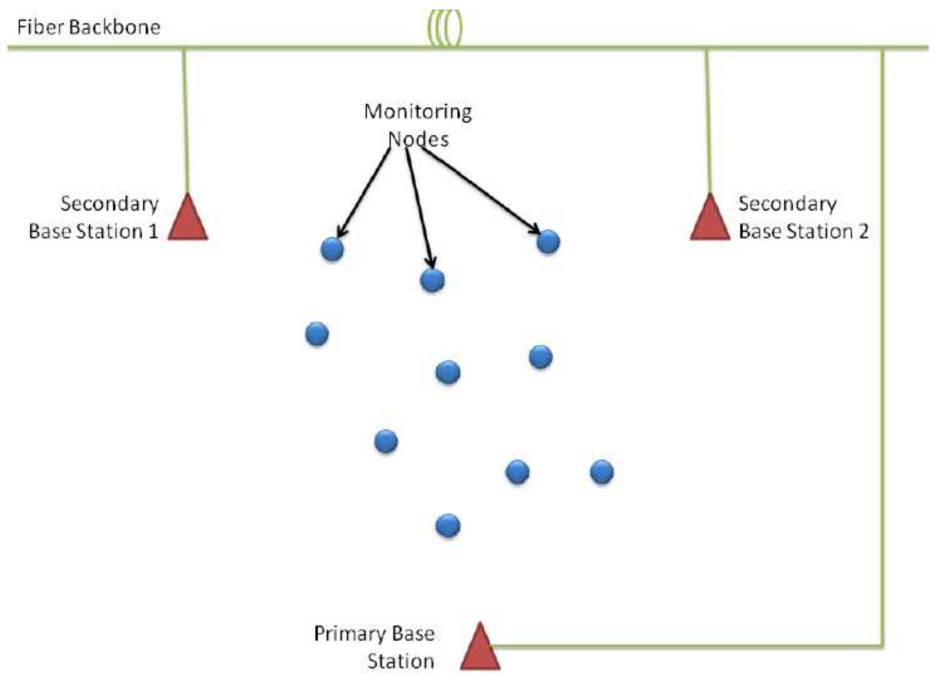

Fig.6.8: Placement of multiple nodes with the base stations along the vertices of an equilateral triangle separated by 120^o

However, before we proceed further, it is necessary that we define some of the terms that we are going to be using frequently in this discussion.

Terms and Definitions

Primary Base Station: This is the base station with which the monitoring nodes communicate under Line-of-Sight communications. This is the one which will handle most of the communications most of the time.

Secondary Base Station: There are two such base stations. These are the base stations with which the monitoring node whose beam has been blocked shall communicate. These are extra base stations that are added for increasing robustness and thus are redundant

Primary Beam: This is the beam that connects the primary base station and the monitoring node.

Secondary Beam: This is the beam that connects the secondary base station and the monitoring node. The secondary beam is selected on the basis of the received signal strength of the received acknowledgement.

Switched Beam Antenna: This antenna has a directive radiation pattern capable of being scanned to a set (typically a power of 2) of angular directions or beam positions, so that the whole sector is divided in several micro-sectors. Each micro-sector has a pre-defined beam pattern with maximum gain placed in the center of the beam. This beam-switching approach matches perfectly with a time-based system (TDM/TDMA), as the BS antenna is illuminating only in the desired direction in the assigned access instant.

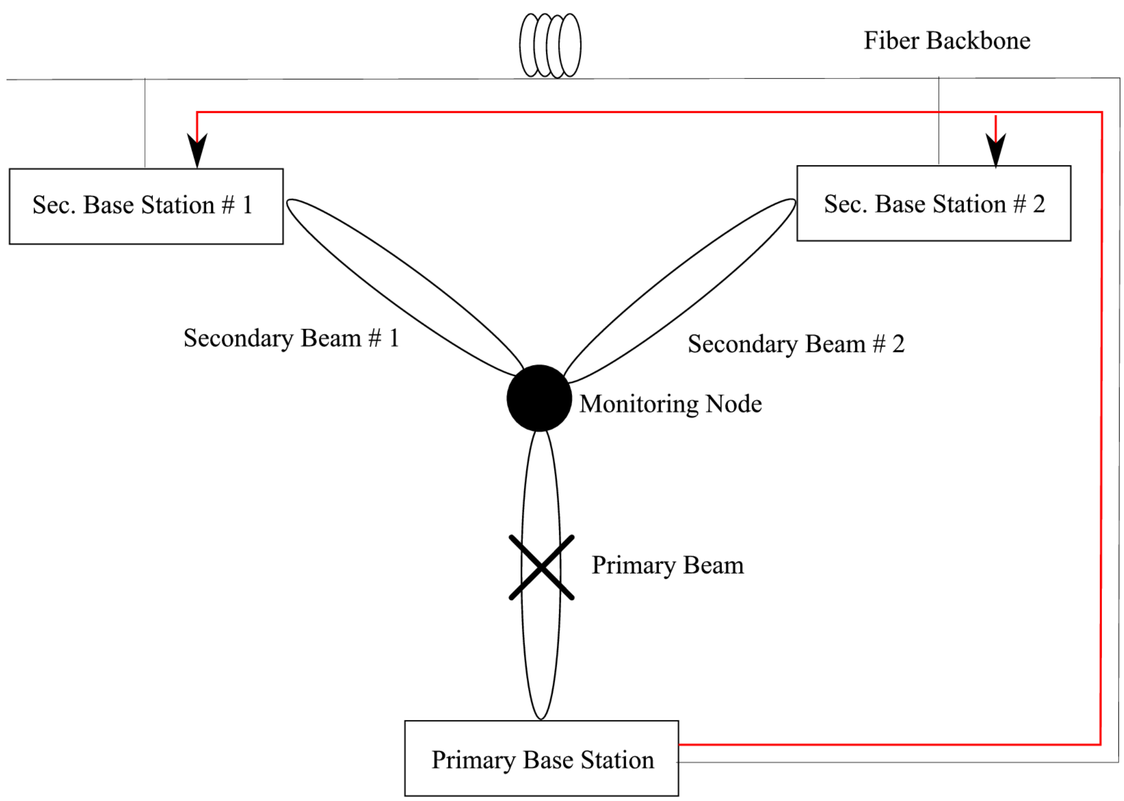

Fig.6.9: When the beam is blocked the base station communicates with other base stations informing them of this fact

Now, the Primary Base Station passes a message via the fiber backbone to the two secondary base stations as shown in Fig 6.9. They now realize that the primary beam has been blocked and that they have to initiate transmission. Included in this message is the node i.d. along with the node timing. Stored in the memory of the two secondary base stations is the maximum intensity beam number connecting the respective base station to the node. Also simultaneously since the node has not received the ACK-REC, it too realizes that the beam has been blocked. It then switches on the beams that correspond to the secondary base stations sequentially.

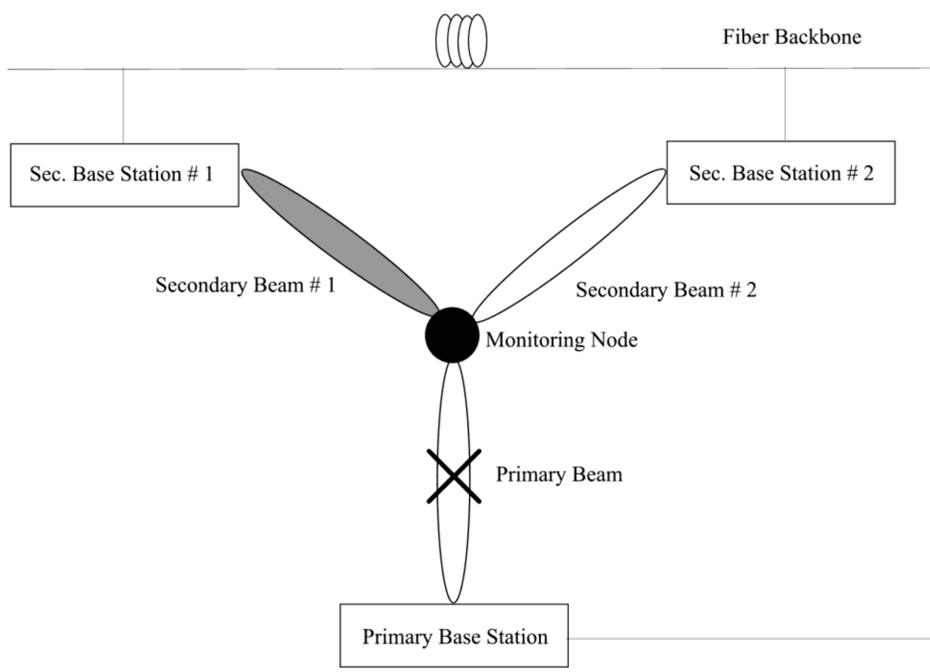

Fig.6.10: The node then exchanges the handshake with the secondary base station # 1 and then uses this to determine signal strength

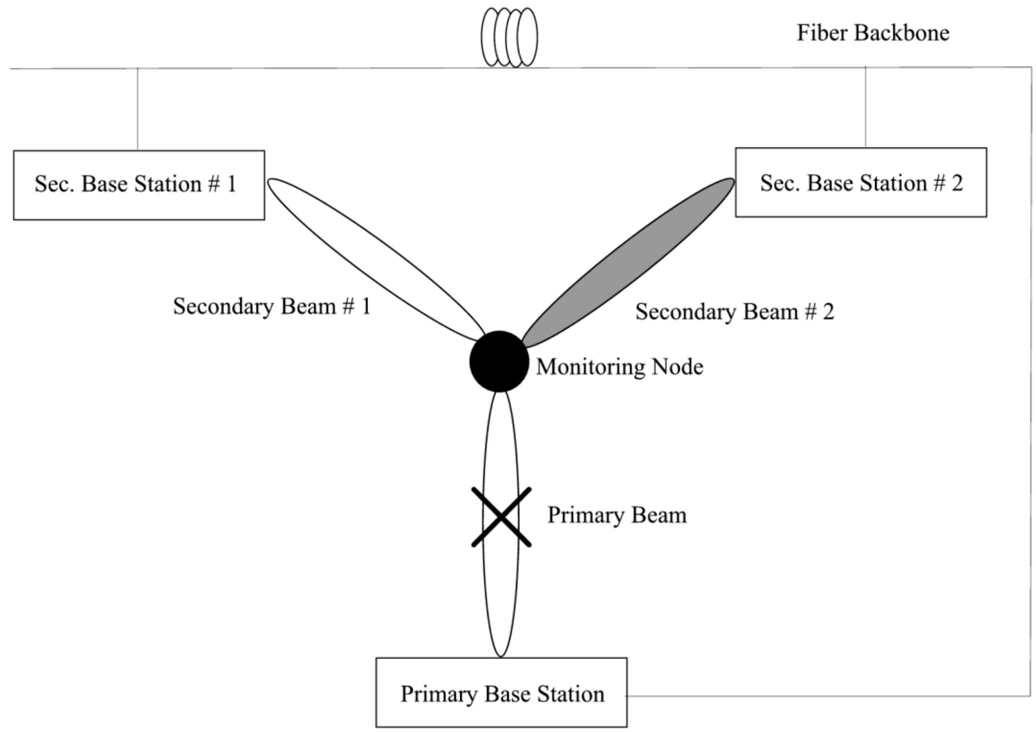

Fig.6.11: The node then exchanges the handshake with the secondary base station # 3 and then uses this to determine signal strength. It then compares the two and uses it to decide which one to communicate with

What happens is as shown in Fig 6.10 and 6.11. The Secondary Base Station # 1 shall output the node i.d. and timing to the node. This data is then processed by the node which shall then emit the ACK signal. The Secondary Base Station # 1 shall then return ACK-REC. The node shall measure the strength of this ACK-REC signal. Then the same procedure is repeated by Secondary Base Station # 2. The node then compares the two signal strengths. It then issues a Tx-Begin signal to the Secondary Base Station with which it intends to begin transmission and sends a ¬(Tx-Begin) to the other Secondary Base Station. Transmission now can begin.

State Transition Diagram

Base Stations

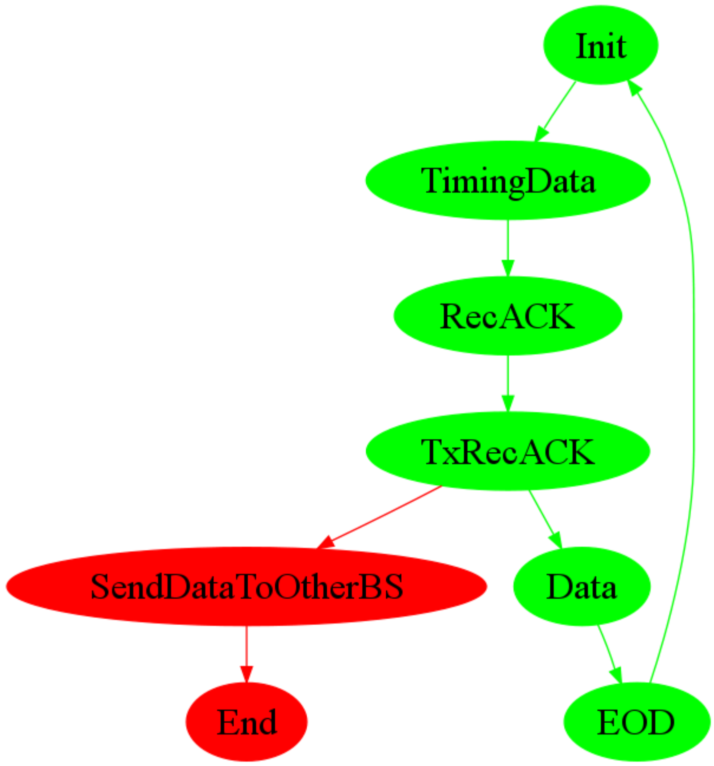

Fig.6.12: State Transition Diagram for the 3 base station case

3 BS	
Protocol State	Primary BS state
INIT	idle
TIMING DATA	WirelessTx
RECACK	wirelessRx
TXRECACK	WirelessTx
DATA	wirelessRx
EOD	wirelessRx
SENDDATATO2BS	OpticalTx
END	Sleep

Table 6.6: Correlating the base station state with the protocol state

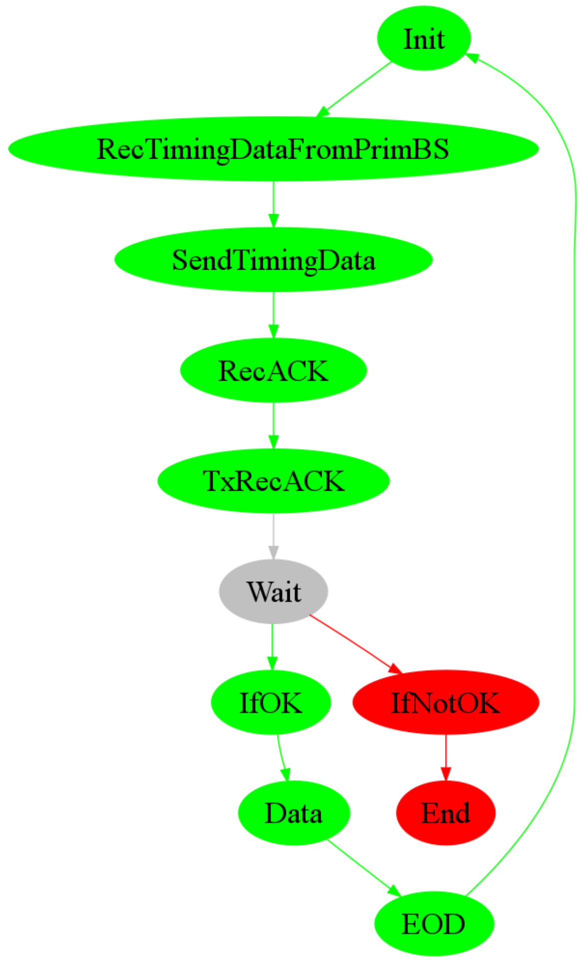

Fig.6.13: State Transition diagram for the secondary base station

3 BS	
Protocol State	Sec BS state
INIT	idle
RXTIMINGDATA	opitcalRx
SENDTIMINGDATA	wirelessTx
RECACK	wirelessRx
TXACK	WirelessTx
WAIT	idle
OK/NOTOK	wirelessrx
DATA	wirelessrx
EOD	wirelessrx
END	sleep

Table 6.7: Correlating Secondary base station state with the protocol state

Monitoring Node

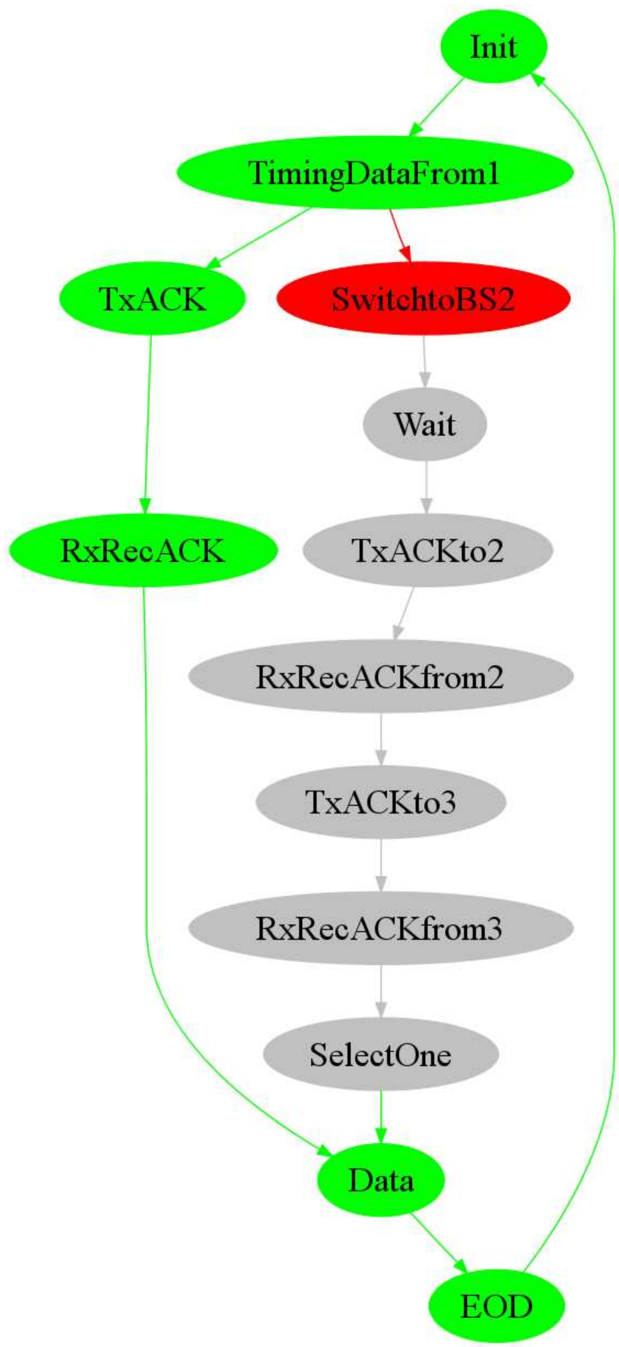

Fig 6.14: State Transition diagram for the node

3 BS	
Protocol state	Node State
INIT	Idle
TIMINGDATAFROM1	Rx
TXACK	Tx
RXRECACK	Rx
DATA	Tx
EOD	Tx
SWITCHTOBS2	Tx+Rx
WAIT	calc
TXACKTO2	Tx
RXRECACKFROM2	Rx
TXACKTO3	Tx
RXRECACKFROM3	Rx
SELECTONE	calc

Table 6.8: The states of the protocol correspond to the specific states of the node

The initial state of both the Base Station and the node is Init during which both of them idle as shown in Figs 6.12 and 6.14. When the timing data is sent by the Base station, it goes into the TimingData state which corresponds to the Wireless-transmit hardware state as shown in table 6.6. The node is then in the RecTimingData state when it receives the timing data as shown in Fig 6.14 and table 6.8. Its own hardware state is Receive. It then moves to the TxACK mode and if the beam is not blocked, the base station hardware subsequently goes into Wireless-Receive mode and the protocol state of the base station is RecACK as shown in table 6.6. The node then transmits the data which the base station receives until the base station transmits EOD and the node receives it.

If however, the beam is blocked, the base station sends the data to the other base station via the fiber using the OpticalTx hardware state (table 6.6) and then goes off to sleep. This timing data is then received by the secondary base station whose hardware is in the OpticalReceive mode (table 6.7). It too sends the timing data to the node and repeats the same steps as shown in Fig 6.13. However, after TxRecACK it goes into idle while it waits for the base station to respond. The behavior of the base station differs depending upon the response it gets from the node. If it is selected then it receives the data from the node. If it is not then it goes off to Sleep as seen in Fig 6.13. This behavior is identical for both base stations.

The node on the other hand receives TxACK to both base stations successively. After receiving the acknowledgement receipt from both, it determines which one has a higher power and transmits data to that particular base station

Medium Access Table

								3 BS case													
	Time Slot	BS no.	Node no.	BS Beam No.	Node Beam no.		Prim. BS Stop				Sec. BS 1 Stop				Sec BS 2 Stop				Node Stop		
Original						Beam 1	Beam 2	Beam 3	Beam 4	Beam 1	Beam 2	Beam 3	Beam 4	Beam 1	Beam 2	Beam 3	Beam 4	Beam 1	Beam 2	Beam 3	Beam 4
	1	1	1	1	2	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
	2	1	2	2	1	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
After first block																					
	1	1	1	1	2	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
	2	3	2	4	2	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	no	yes	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
New Original																					
	1	1	1	1	2	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
	2	3	2	4	2	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	no	yes	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
After sec. block																					
	1	1	1	1	2	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
	2	2	2	1	4	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
	3	1	3	1	3	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes	yes

Table 6.9: Medium Access Table for the 3 Base Station case

Table 6.9 shows the medium access table for the three base station case. The entries shown above describe the situation that occurs when the primary beam gets blocked. The transmission then may occur through either the second or the third base station. Depending on signal strength the third base station was chosen. Communication takes place using the 4^{th} beam of the third base station and the 2^{nd} beam of the node. When this path gets blocked we then use the 1^{st} beam of the second node and the 4^{th} beam of the first node to communicate.

Simulation

Assumptions

1. Power received by the Secondary Base Station and the Primary Base Station is identical.

2. All the nodes are at a fixed distance from all the three Base Stations.

3. Signal is either perfectly received or not received at all i.e. a binary event.

4. The blocking of beam is a purely random event. It occurs once every ten transmissions to one and only one node. This node is chosen at random. The transmission at which the blocking occurs is also randomly chosen.

5. The Secondary Base Station is chosen randomly i.e. coin toss.

6. Effective fiber BS to BS spacing is assumed to be 10 m which gives rise to 50 nsec BS to BS delay assuming the fiber index of refraction is 1.5.

Simulation Parameters

Protocol # 1 - 3 BS	
BS-Bs delay	50
Determining time	66.66667
Processing delay 1	100
Sec BS 1 Data Ex	66.66667
Sum 1	283.3333
Processing delay 2	100
Sec BS 2 Data Ex	66.66667
Sum 2	450

Table 6.10: Simulation Parameters

Simulation Methodology

Using a random number generator select a number between 1 and 10 to denote the time slot when the blocking shall occur. We assume that once every 10 iterations the beam is blocked. This is because we are designing for the worst case scenario. A blockage once every 10 transmissions shall denote a beam blockage once every 25 to 30 seconds. Design a coin toss simulator to determine which base station is selected. Delay in case Secondary Base Station # 1 is selected is calculated as shown above as is the case for Base Station # 2. The result is as shown in Fig 6.15

Simulation Results

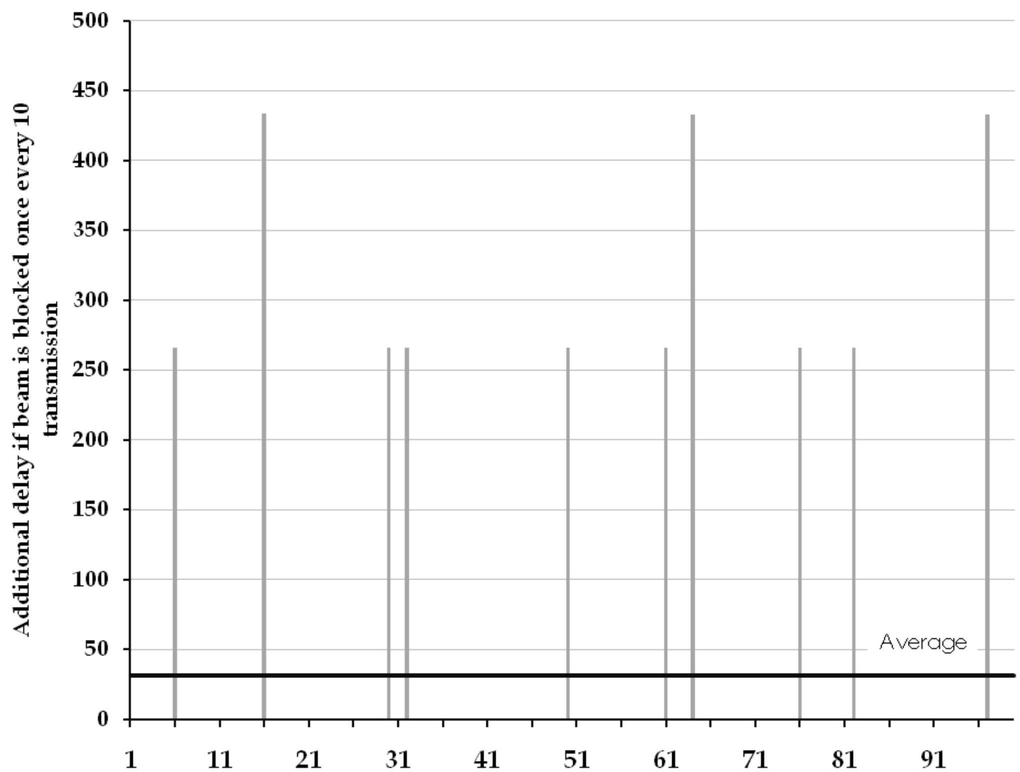

Fig. 6.15: Additional delay if the beam is blocked once every 10 transmissions. X axis contains iteration number

Take the above 100 iterations and then take the average. This gives us one data point. We perform this 20 times. We then repeat the experiment if the blockage were to occur once every 20 transmissions and once every 50 transmissions. The result is as shown in Fig 6.16

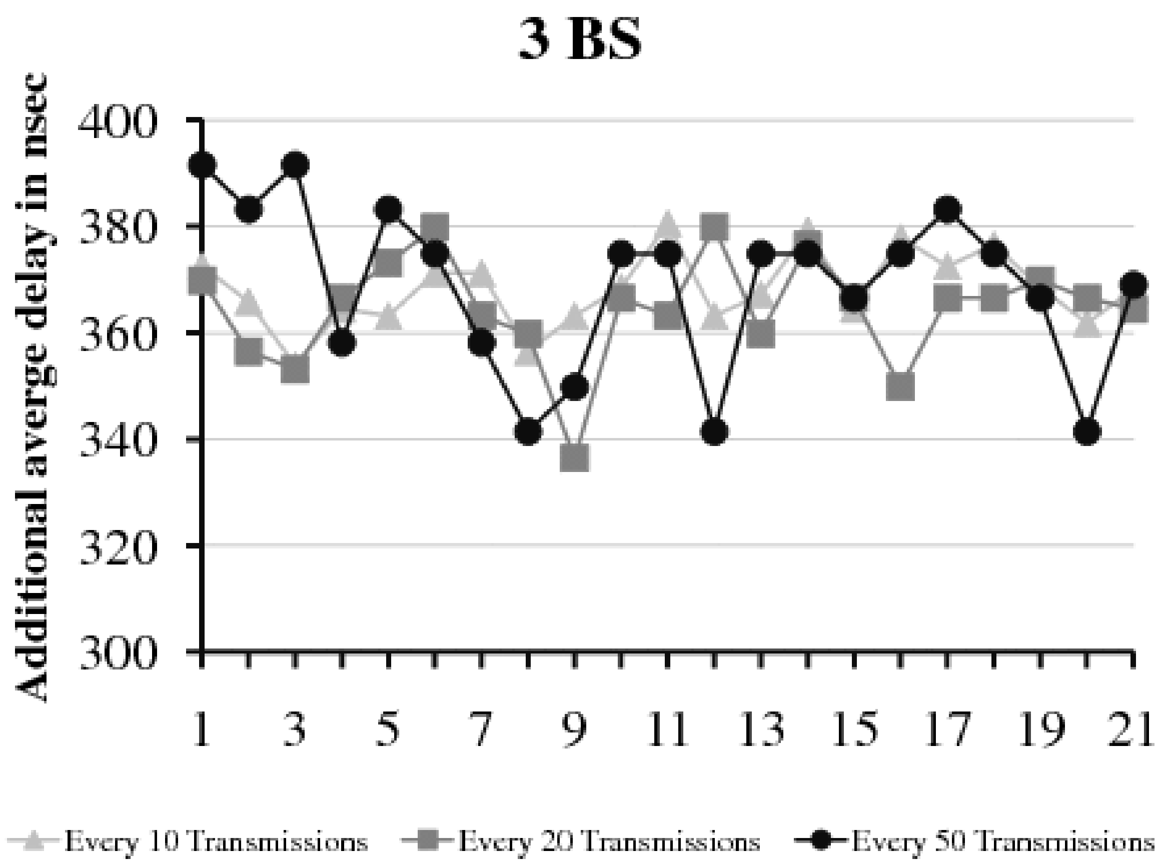

Fig 6.16: Average Additional delay. X axis denotes the iteration number

From Fig 6.16 it is evident that the delay is between 340 ns to 400 ns which is comparable to the single base station case. There does not appear to be a strong dependence upon the number of times the beam is blocked.

But there are two other advantages to this method. Firstly we have assumed in the single bases station case that either a 6 sector or an 8 sector switched beam antenna is used. Hence the delays appear comparable. But in order to extend the range, it is advisable to use narrow beamwidths for the sectors. This implies that the number of sectors shall increase increasing delay. However, in this case, we can use very narrow beams without significantly increasing delay. Thus there is overall range extension. In fact it is preferable to use narrow beams as it shall reduce the probability of blockage. Also this technique guarantees end to end delivery, which is very important in the applications that we have considered. This is significantly different compared to the one base station, where a significantly large object could block multiple sector beams.

Effect of moving obstructions

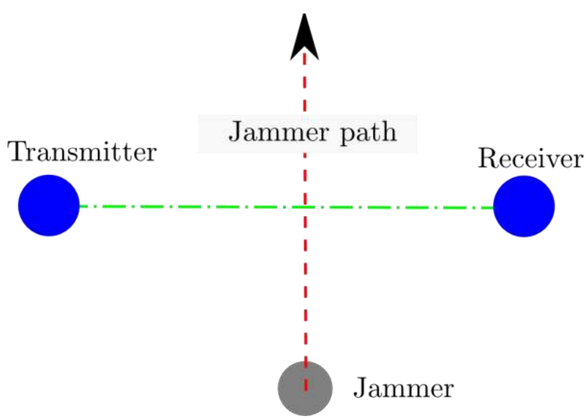

Fig. 6.17: Moving obstruction that blocks the path between transmitter and receiver

Hitherto we have considered the effect of a stationary obstruction on the network in the case a single base station is used and in the case 3 base stations are used in order to provide redundancy. The two cases appear to be nearly identical in all respects. This raises the question of complexity and cost. The network utilizing three base stations clearly involves installing and maintaining three base stations. This clearly adds to cost and complexity. This might cause one might wonder about the benefits of this scheme. One of the principal benefits of this scheme is that the added redundancy ensures that at all times, under all sizes of blockage, transmission shall be maintained especially in the case of moving obstruction. In particular, we consider the network shown in Fig 6.17.

This is illustrated by the plots 6.18 to 6.20 that plot the additional loss caused if the beam is blocked. As we can clearly see in the case of a single base station, a moving obstruction shall at some point or another block all the beams as shown in Fig 6.18, thus necessitating another handshake protocol and further delays and data loss. However, this problem is largely alleviated in the case of three base station network as one of the beams is never blocked by an obstruction moving along a straight path as shown in Fig 6.20

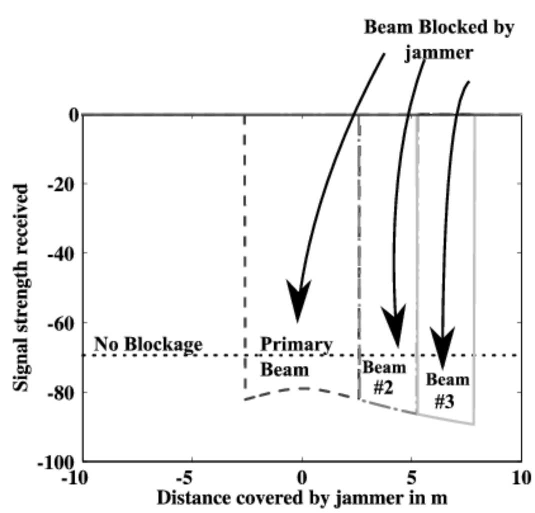

Fig. 6.18: The drop in signal strength as the object moving forward progressively blocks the first second and third beams of a six sector switched beam antenna

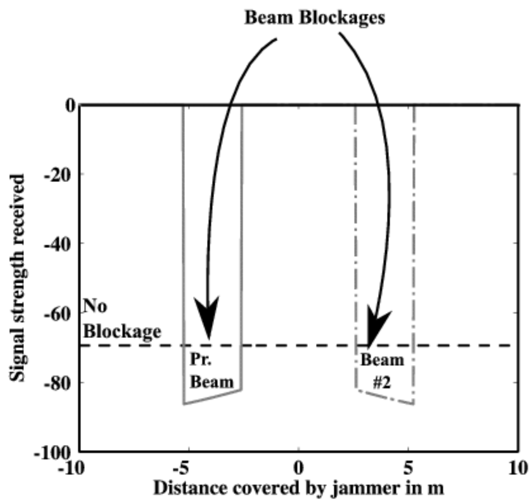

Fig.6.19: The beam connecting the node to the secondary base station may be blocked if the object is moving along a straight line that lies on both beams

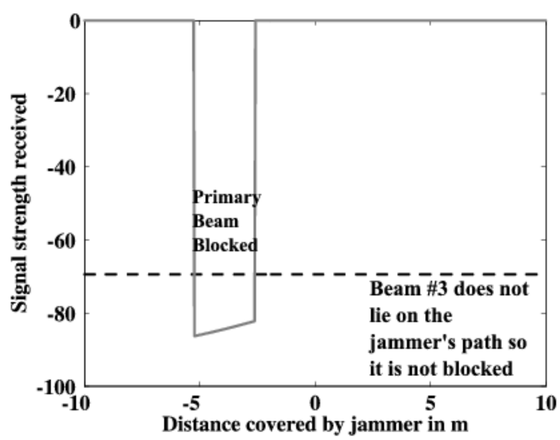

Fig.6.20: The beam connecting the node to the secondary base station may be blocked if the object is moving along a straight line that lies on both beams

2 Base Station Case

Diagram Representation

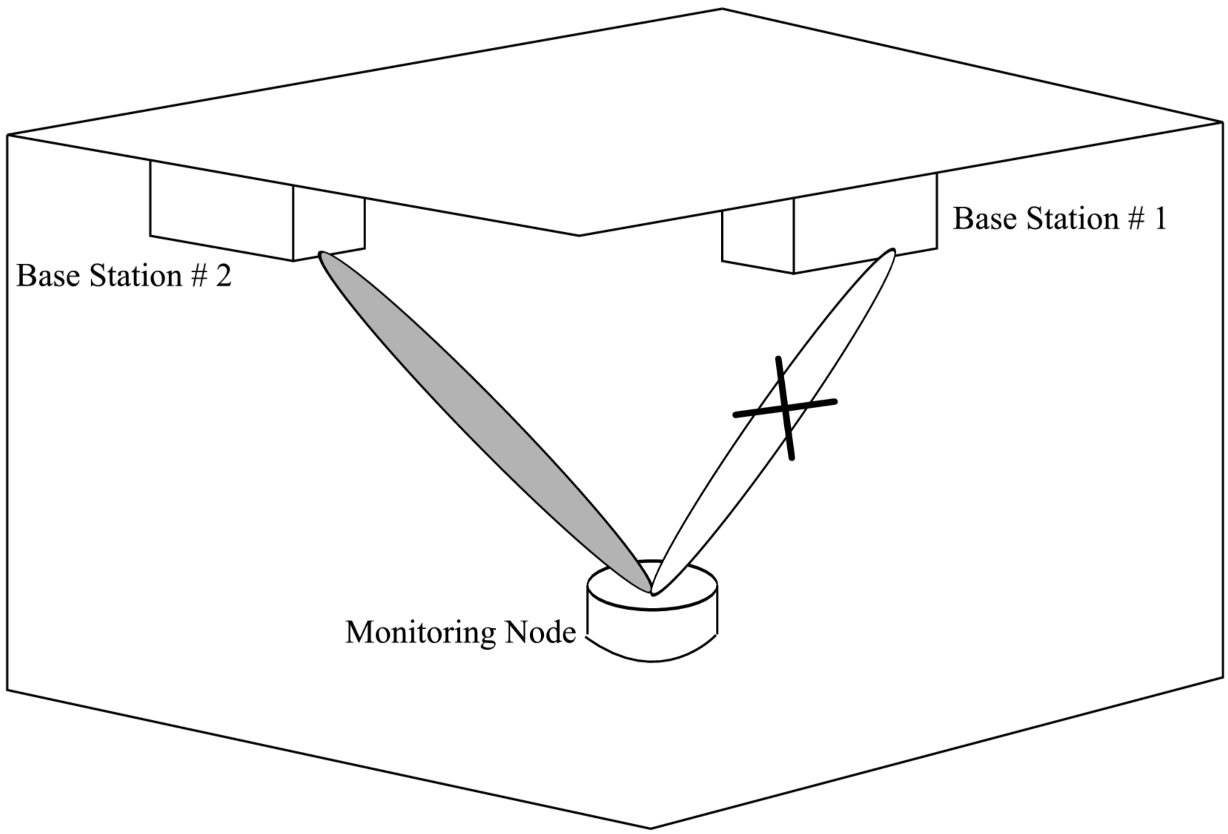

Fig.6.21: Representation of the network employing 2 base stations

Description

In the previous sections we considered the effect of using multiple base stations to guarantee delivery in case of beam blockage. Three base stations placed at 120^o with respect to each other did certainly provide the desired mechanism. However, there is another way of accomplishing the same. We do so by using just 2 base stations as shown in Fig 6.21. In the previous section we assumed that the space over which the nodes were distributed was effectively in 2 dimensions. However, in a

3 dimensional space it still might be possible to accomplish the same guaranteed end to end delivery without using so much redundancy thereby reducing installation and maintenance costs. The operation of such a scheme is explained in the state machine diagram shown in Fig 6.22, 6.23 and 6.24. In this case, as in the case of the 3 base stations case, if the beam were to get blocked the primary base station informs the secondary base station of the same using the fiber backbone. The secondary base station then initiates communication with the primary base station by sending the timing details to the node. The node which has not yet received the ACKREC now switches on the beam that faces the secondary base station, receives the timing data, issue RECACK and then continues with its communication as it would have done in the case of the primary base station

State Machine

Base Station

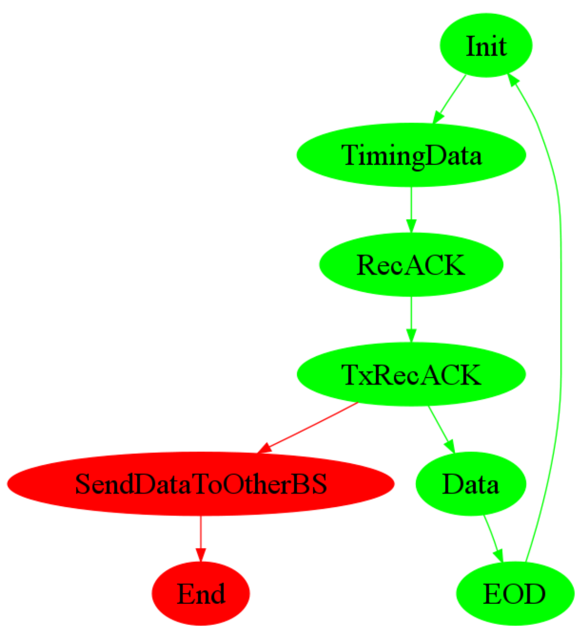

Fig 6.22: State transition diagram for the primary base Station

2 BS	
Protocol State	Primary BS state
INIT	idle
TIMINGDATA	WirelessTx
RECACK	wirelessRx
TXRECACK	WirelessTx
DATA	wirelessRx
EOD	Rx
SENDDATATO2BS	Optical Tx
END	Sleep

Table 6.11: Correspondence of the protocol state with the primary base station state

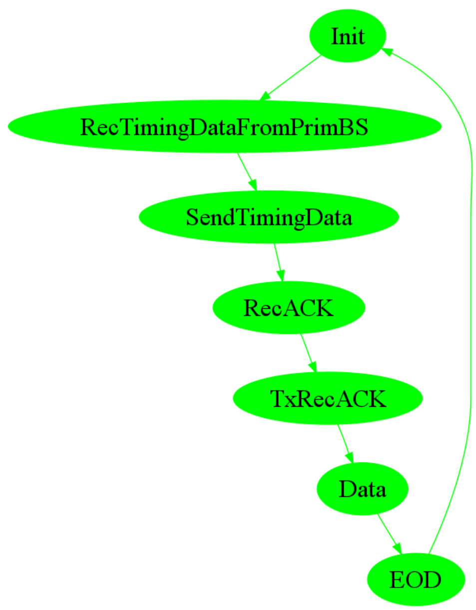

Fig. 6.23: State Transition diagram of the Secondary Base station

2 BS	
Protocol State	Sec BS state
INIT	idle
RECTIMINGDATA	OpticalRx
SENDTIMINGDATA	WirelessTx
RECACK	wirelessRx
TXRECACK	WirelessTx
DATA	wirelessRx
EOD	wirelessRx

Table 6.12: Correspondence of the protocol state with the secondary base station state

Node

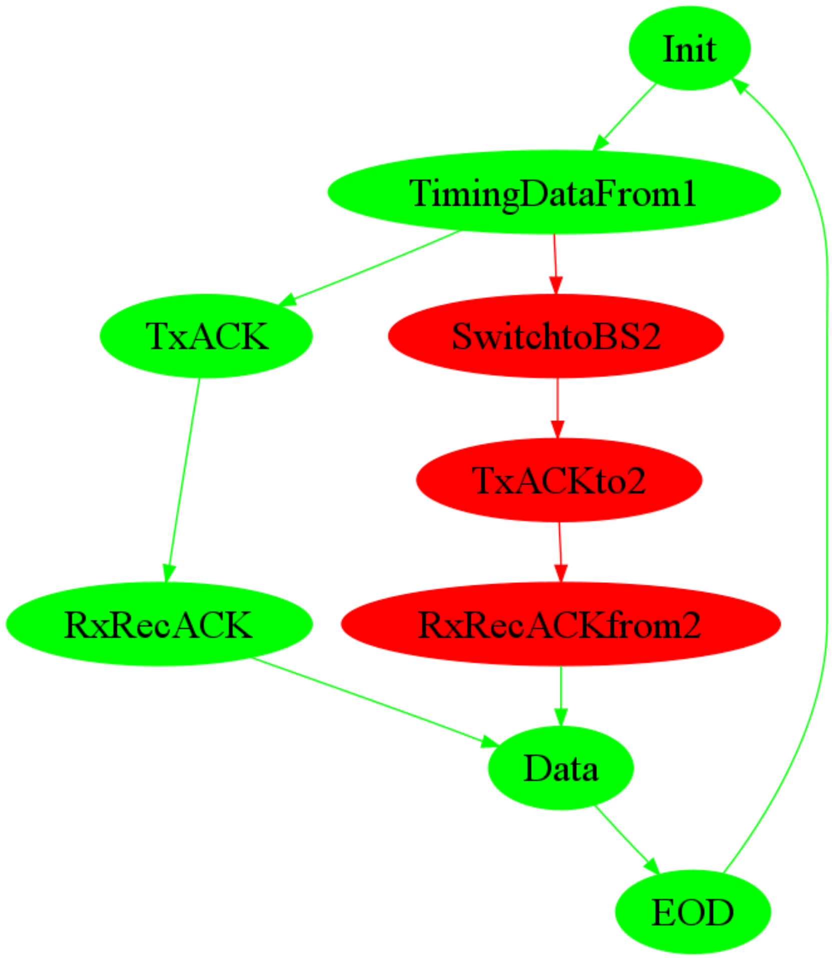

Fig.6.24: Node state transition diagram

2 BS	
Protocol state	Node State
INIT	idle
TIMINGDATAFROM1	rx
TXACK	tx
RXRECACK	rx
DATA	tx
EOD	tx
SWITCHTOBS2	Tx+Rx
TXACKTO2	tx
RXRECACKFROM2	rx

Table 6.13: Correspondence of the protocol state with the node state

As seen in Figures 6.22, 6.23 and 6.24, the initial state of both the Base Station and the node is Init during which both of them idle. When the timing data is sent by the Base station, it goes into the TimingData state which corresponds to the Wireless-transmit hardware state as explained in table 6.11. The node is then in the RecTimingData state when it receives the timing data. Its own hardware state is Receive as shown in table 6.13. It then moves to the TxACK mode as shown in Fig 6.22 and if the beam is not blocked, the base station hardware subsequently goes into Wireless-Receive mode according to table 6.11 and the protocol state of the base station is RecACK according to Fig 6.22. The node then transmits the data which the base station receives until the base station transmits EOD and the node receives it as shown in Fig 6.22 and 6.24.

If however, the beam is blocked, the base station sends the data to the other base station via the fiber using the OpticalTransmit hardware state and then goes off to sleep as seen in Fig 6.23. This timing data is then receieved by the secondary base station whose hardware is in the OpticalReceive state as shown in table 6.12. It too sends the timing data to the node and repeats the same steps as the first base station and receives data from the node

Medium Access Table

				2 BS													
	Time Slot	BS number	Node no.	BS Beam No.	Node Beam no.		Prim. BS Stop				Sec. BS Stop				Node Stop		
						Beam 1	Beam 2	Beam 3	Beam 4	Beam 1	Beam 2	Beam 3	Beam 4	Beam 1	Beam 2	Beam 3	Beam 4
Original																	
	1	1	1	1	2	no	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
	2	1	2	2	1	yes	no	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	yes	yes	yes	yes	no	yes	yes	yes
				2 BS													
	Time Slot	BS number	Node number	BS Beam No.	Node Beam no.		Prim. BS Stop				Sec. BS Stop				Node Stop		
After 1st blockage																	
	1	1	1	1	2	no	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
	2	2	2	3	3	yes	yes	yes	yes	yes	yes	no	yes	yes	yes	no	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	yes	yes	yes	yes	no	yes	yes	yes
				2 BS													
	Time Slot	BS number	Node number	BS Beam No.	Node Beam no.		Prim. BS Stop				Sec. BS Stop				Node Stop		
New Original																	
	1	1	1	1	2	no	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
	2	2	2	3	3	yes	yes	yes	yes	yes	yes	no	yes	yes	yes	no	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	yes	yes	yes	yes	no	yes	yes	yes
				2 BS													
	Time Slot	BS number	Node number	BS Beam No.	Node Beam no.		Prim. BS Stop				Sec. BS Stop				Node Stop		
After 2nd blockage																	
	1	1	1	1	2	no	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
	2	1	2	2	1	yes	no	yes	yes	yes	yes	yes	yes	no	yes	yes	yes
	3	1	3	1	3	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	4	1	4	2	4	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	no
	5	1	5	3	1	yes	yes	no	yes	yes	yes	yes	yes	no	yes	yes	yes

Table 6.14: Medium Access Table for the 2 Base Station case

Shown above in table 6.14 is the medium access table for the 2 bases station case. In this we observe that when the beam pertaining to the primary base station is blocked i.e. the path comprising of beam no. 2 of the base station and beam no. 1 of the node, communication is switched to beam no. 3 of base station 2 and beam no. 3 of the node. This communication takes place until this beam is blocked and then we revert back to base station 1, to continue communication. This of course assumes that by this time the path to base station 1 has been cleared

Simulation

Simulation Parameters and Methodology

The simulation parameters are evaluated in a fashion similar to that in the previous two cases. The methodology is used is also identical. The results are as shown in Fig 6.25

Simulation Results

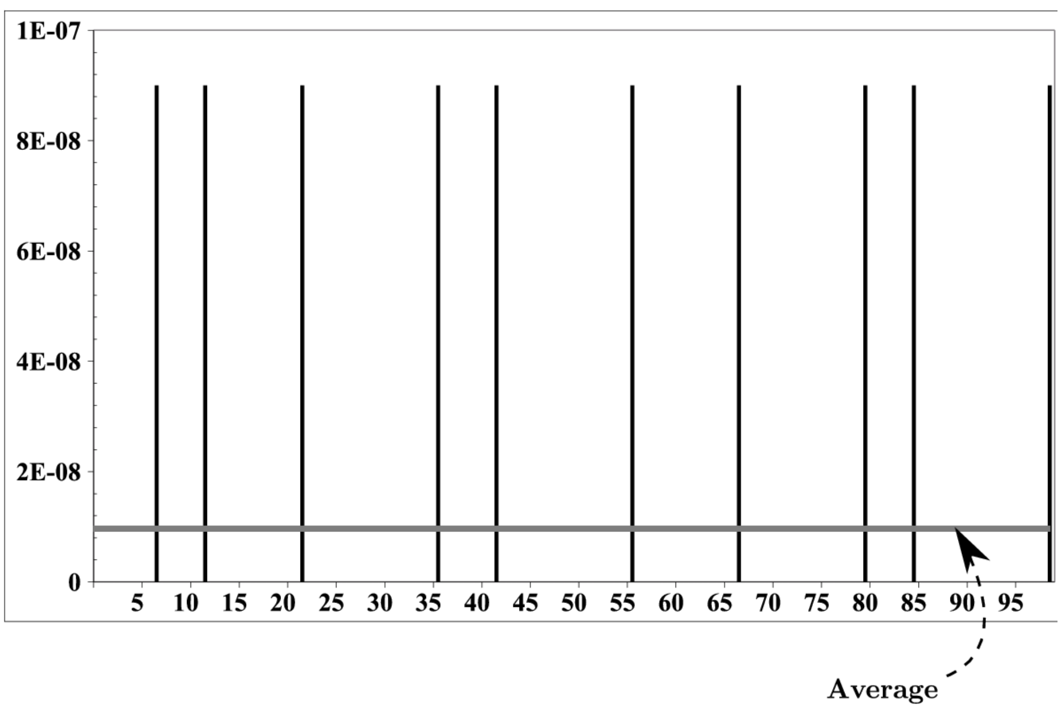

Fig. 6.25: Additional delay caused by the protocol in the 2 base station case. The x axis denotes the iteration number

The results in this case as shown in Fig 6.25 differ in one significant respect from the previous two cases as shown in Figs 6.6, 6.7 and 6.15. In this case no selection is required to be made. Hence we either have zero additional delay in case of normal transmission or a fixed value of delay in case of blockage. Hence the average value remains the same irrespective of number of iterations.

Position of the second base station

Loss X Blockage Probability Calculation

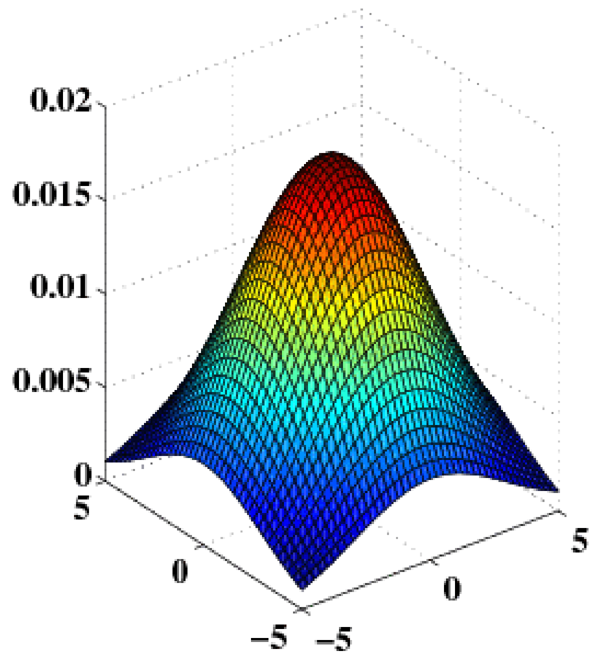

Fig. 6.24: 2 dimensional Gaussian function with zero mean

Now in the case of 3 base stations, the probability of all three being blocked especially as they are positioned 120^{o} apart from each other. Now in the case when only two base stations are involved, the probability of blockage depends upon the location of the second base station. We are assuming that a finite sized object blocks the beam. This implies that the probability of blockage is maximum at the center. As we move further away from the primary base station, the probability of blockage decreases, reaching finally a zero probability at infinity. We model this blockage probability as a Gaussian function in 2 dimensions. The formulation is as follows:

In the 2 dimensional nonsingular case, the probability density function with mean (0,0) is given by

$$f(x,y) = \frac{1}{\boldsymbol{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}}} \exp\left(-\frac{1}{2(1-\rho^2)}\left[\frac{x^2}{\sigma_x^2} + \frac{y}{\sigma_y^2} - \frac{2\,\rho\,x\,y}{\sigma_x\sigma_y}\right]\right)$$

Now if ρ=0 then,

$$f(x,y) = \frac{1}{\boldsymbol{2\pi\sigma_x\sigma_y}} \exp\left(-\frac{1}{2}\left[\frac{x^2}{\sigma_x^2} + \frac{y}{\sigma_y^2}\right]\right)$$

The results are as plotted in MATLAB © as shown in Fig 6.26

Single Monitoring Node

Let us consider the case when a single monitoring node is used. Now, we are faced with the following problem. As is evident from the previous graph, the further we move away from the central node, the lower the probability of blockage. However, the further we move away, the loss may also be higher resulting in a higher BER. The loss depends on the relative position of the monitoring node with respect to the primary base station. The node location is chosen at random, while the base station location is fixed at the origin, as in the previous graph the room is assumed to extend from -5 m to 5m in both x and y directions and 10 m in the z direction

The loss as a function of distance and the probability as a function of distance are plotted. We seek to minimize this function. We plot contours of the above mentioned product so as to create a “topographical map”, as it were, of the terrain as shown in Fig 6.27. Placing the second base station along any of the contours will result in an identical value of the Loss× Blockage Probability function.

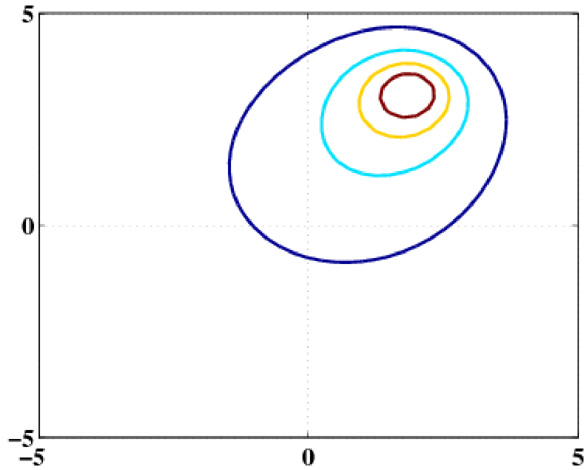

Fig.6.27: Base Station is placed at (0,0). The node position is selected at random. Contour plot of Loss × Blockage Probability

Multiple Monitoring Nodes

Note in our network we have more than one node. We consider the case of 5 monitoring nodes that are randomly. The projection of such an arrangement in 2 dimensions is shown in Fig 6.28

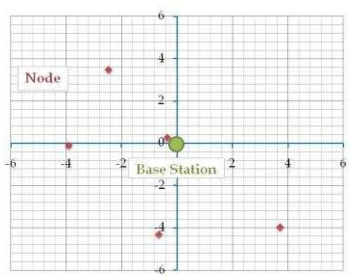

Fig.6.28: 5 randomly placed nodes with the Base Station at the origin

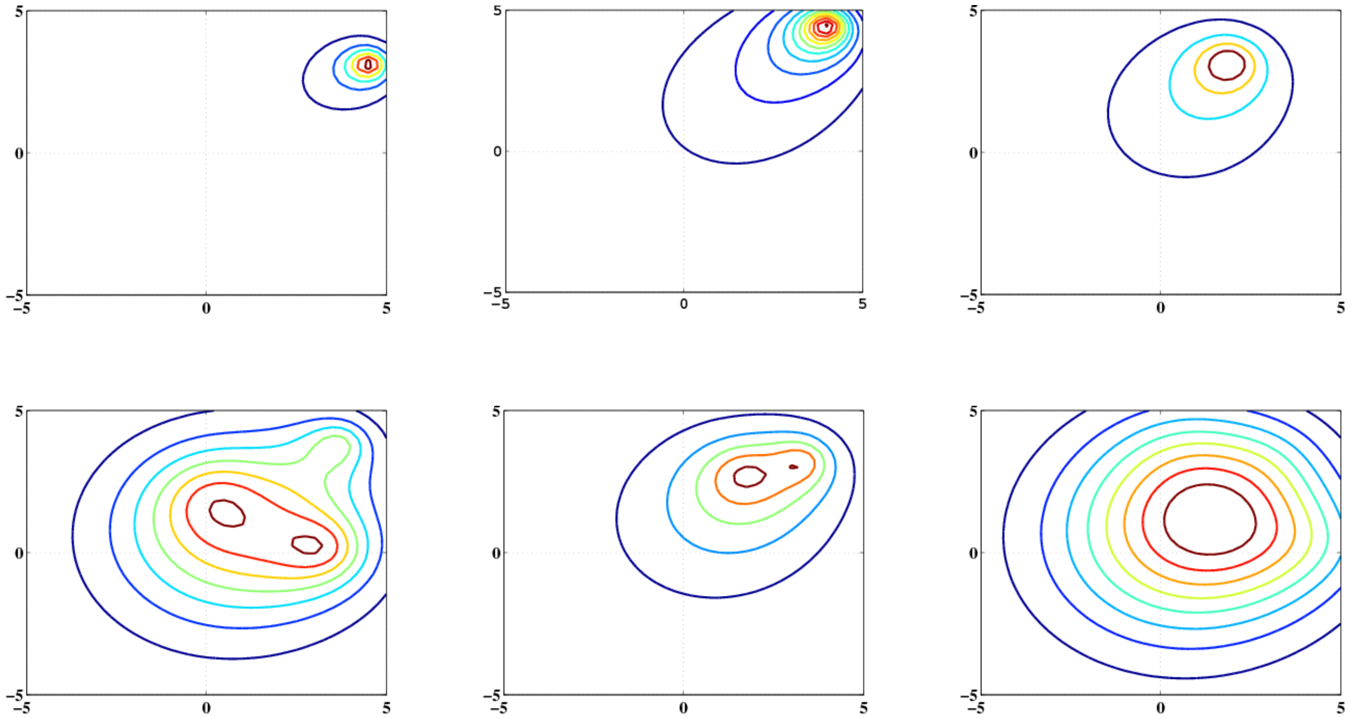

Fig 6.29: Contour plots of the loss × blockage probability for different node arrangements

We thus seek to minimize the loss × blockage probability product. We now run 6 iterations of the same algorithm in order to locate the optimal point. As is evident from the Fig 6.29, the suitable point varies quite dramatically depending on node placements. Since the hardware to implement the protocol was not yet available at the time of writing, it is difficult to experiment and find out the ideal location. This implies that reliable mathematical techniques need to be developed in order to determine the location of the secondary base station. These must methods must be in the form of algorithms that work irrespective of the positioning of the nodes.

Location of the secondary base station - Getting Initial Iterate

We now consider how to generate the position of the secondary base station. We do so by the following procedure. Consider the case of five monitoring nodes that are randomly placed ranging from -5 to 5 m in all three directions. The base station is placed at the point (0,0,0) as shown in Fig 6.30.

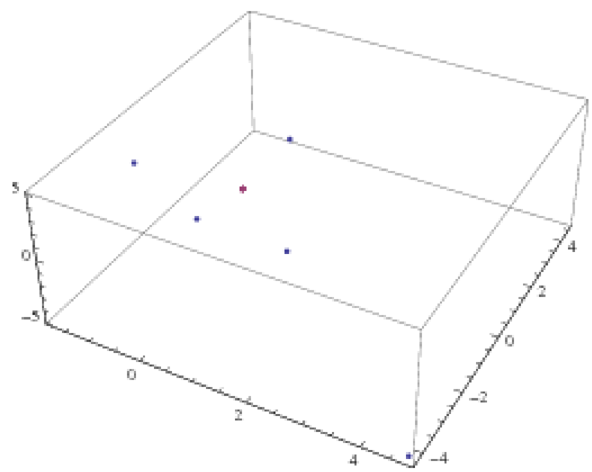

Fig.6.30: 5 randomly placed nodes in 3 dimensional space (blue) and the base station at the point (0,0,0)

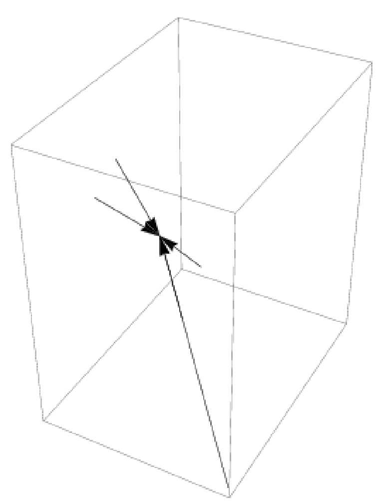

Fig.6.31: Draw vectors from the nodes to the base station.

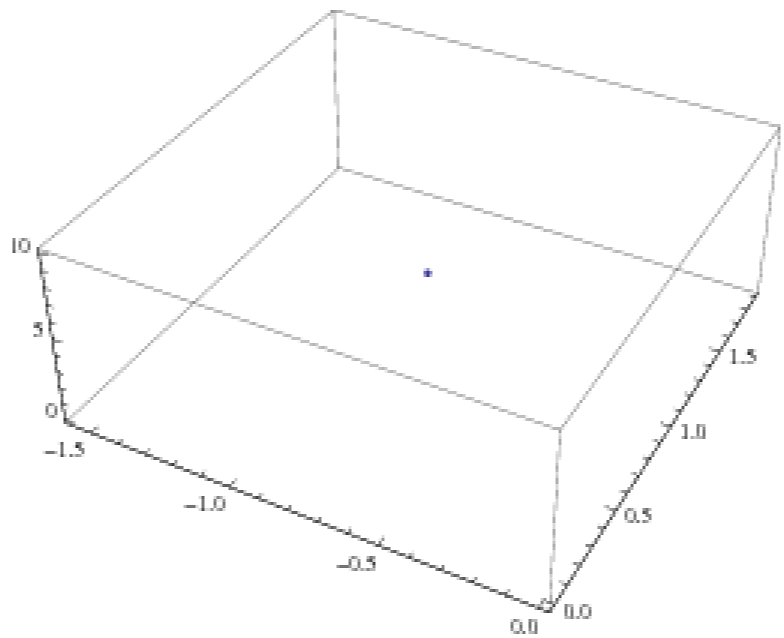

Fig 6.32: Invert the vectors and take the average value of the x and y coordinates

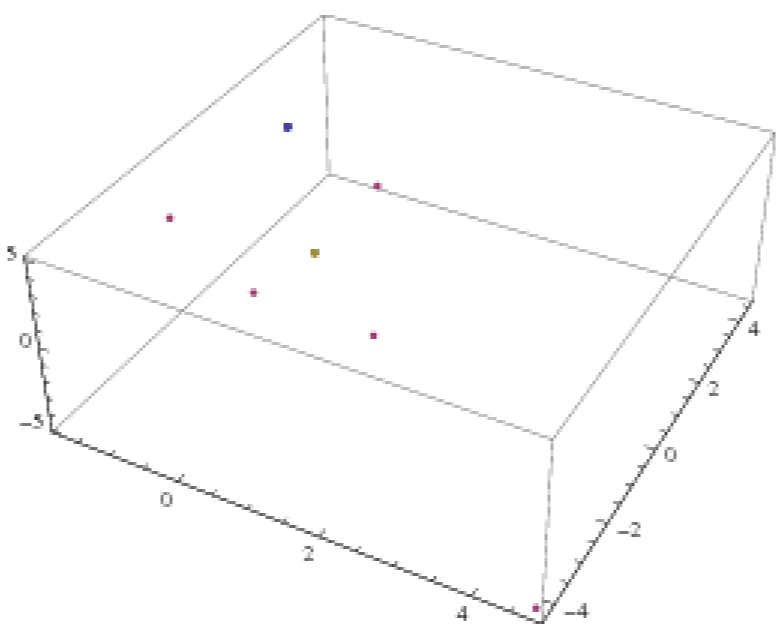

Fig 6.33: Nodes (red) Primary base station (blue), Secondary base station (yellow)

The procedure for finding the location of the secondary base station now proceeds as follows. We construct vectors from the nodes to the primary base station as shown in Fig 6.31. This gives us a notion about the distance and the directionality between the nodes and the base station. Now we would like to find the point least likely to be affected by beam blockage. We do so by inverting these vectors and taking the average as shown in Fig 6.32. The argument is that a point that is diametrically opposite to the base station would be requiring an extremely large object to block. In some cases this may not even be possible. This gives us the desired point. Now we plot this point on the contour plot as shown in Fig 6.34.

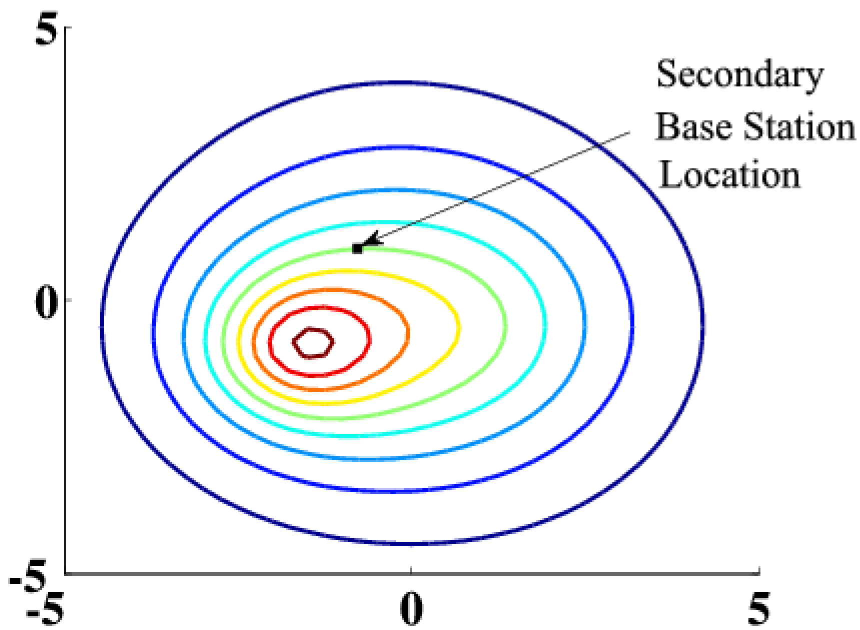

Fig.6.34: Location of the secondary base station on the contour plot

Now, when we consider the location of the secondary base station in Fig 6.34, we realize that the location on the Loss × Blockage probability contour plots is not optimal. Now if we are to find the correct location in a reliable way, we need a methodology of finding this position irrespective of the location of the sensor nodes.

Improving the iterate – Newton's Method

In mathematics, Newton's method is a well-known algorithm for finding roots of equations in one or more dimensions. It can also be used to find local maxima and local minima of functions, as these extrema are the roots of the derivative function.

We now see the algorithm given below. It describes the methodology for finding the root. Essentially what we are doing is trying to reduce the value of the gradient which serves the function of the derivative in higher dimensions to a value below a certain error threshold. This is akin to reducing the derivative to zero. The resulting value of the function then is at the desired extremum. A detailed explanation is given in Appendix A.

Algorithm [29,30]

newton(x; f ; τ)

1. $r_0 = \|\nabla f(x)\|$

2. Do while

  2.1 Compute $\nabla^2 f(x)$

  2.2 Factor $\nabla^2 f(x) = LL^T$

  2.3 Solve $LL^T s = -\nabla f(x)$

  2.4 $x = x + s$

  2.5 Compute $\nabla f(x)$.

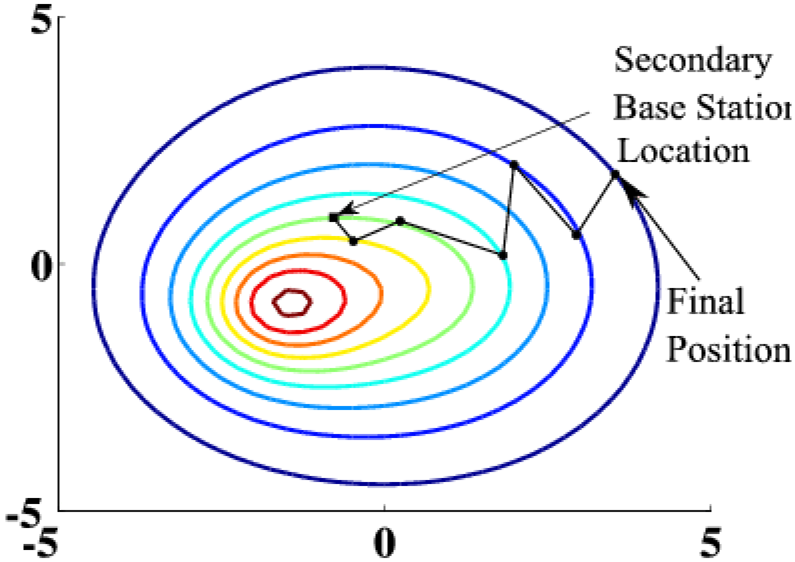

Fig. 6.35: Variation of position of the secondary base station with iterations

The effect is seen in the Figure 6.35. As can be clearly seen from the Fig 6.35, at the first iteration the algorithm is not able to find out which direction is the direction it should move to minimize the function. It however, recognizes this and rectifies itself in the second iteration. As the iterations increases the position is progressively refined till we reach a point of minimal Loss × Blocking probability. This gives the final position as shown in Fig 6.35. The advantage of the approach we have described is that this methodology can be applied to any arbitrary network conFiguration.

Comparative Analysis

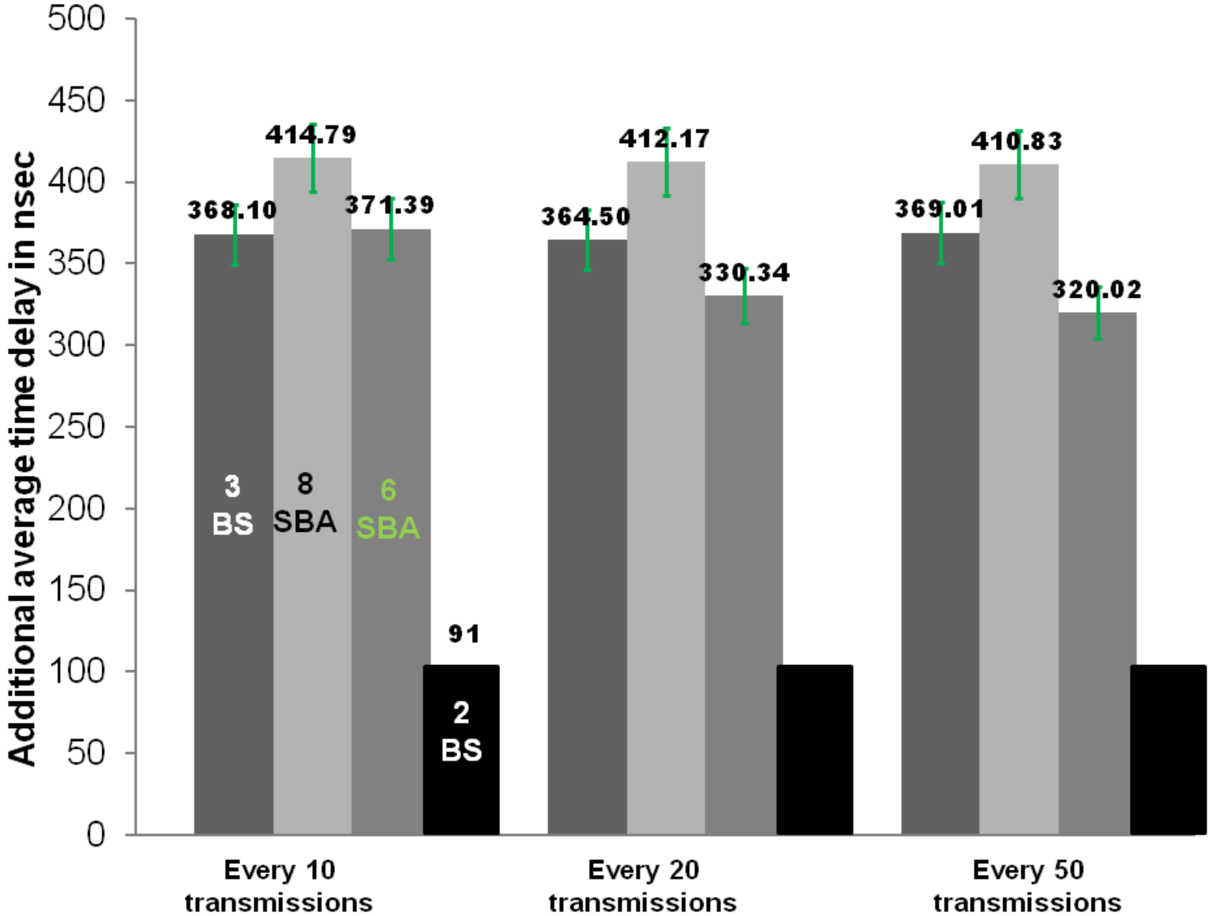

Fig. 6.36: Histogram of the average delay. The x axis indicates the number of transmissions per blockage that occurs.

We collect the average value of the additional delay caused by the protocol for the Single base station 6 and 8 sector switched beam antenna form Fig 6.6 and 6.7 and the same value for the three base station case from Fig 6.15. the average value for the 2 BS case is also computed. As can be seen from the Figure, the 2 base station case has lesser additional average delay than the other two cases. The additional delay for the three base station case is marginally better for the three base station case compared to the 8 sector switched beam antenna. It is also marginally worse than a six sector switched beam antenna. The histogram also reveals a minimal difference with the number of blockages.

Sensitivity Analysis

It is important to note that in calculating these delays we have made certain assumptions about the values of the component delays. This was essential as the hardware that would enable such a network does not yet exist. Also certain assumptions were made about the average node to base station distance and base station to base station distance. These assume certain network geometry. However, since we are not aware of the exact details which could cause a considerable difference in the observed results. We hence decided to study the influence of varying the individual component delays on the overall performance. The results are summarized below.

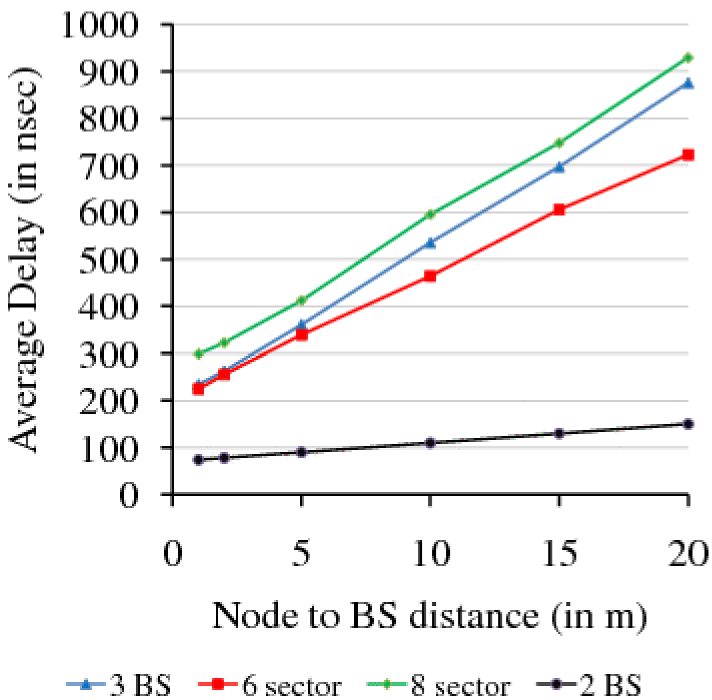

Fig.6.37: Variation in average delay with average node to Base station distance

Fig 6.37 shows that as the node to BS distance increases, the effect on average delay is more or less linear. It is also note worthy that the effect on the two base station case is the least. The delay for the 3 base station case is comparable to that of the 6 sector switched beam antenna at lower values of node to base station distance, however, at greater distances delay increases much more substantially for the 3 base station case

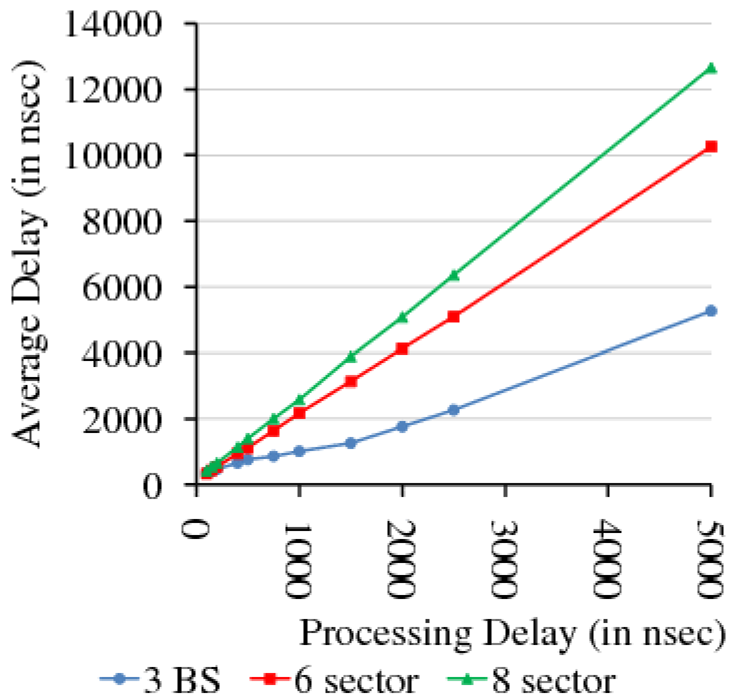

Fig.6.38: Variation in average delay vs. processing delay that occurs in handshake operation

Now, in order to handle the non line of sight condition as explained earlier, we are using a handshake protocol. This involved the node and the base station exchanging timing information, Acknowledge and Acknowledge Receive signals. The signals involve the signals being processed by the on board microprocessor. The effect of this delay is plotted in Fig 6.38. At lower values of processing delay, the three show comparable performance. However, at larger values the 3 Base Station case is least affected. The delay rises sharpest in the case of the 8 sector switched beam antenna and moderately so in the case of the 6 sector switched beam antenna

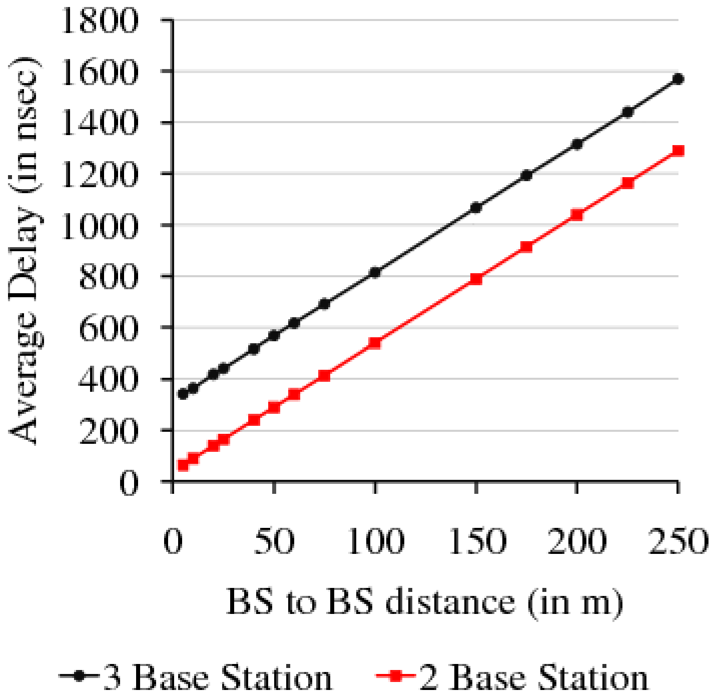

Fig.6.39: Variation in average delay as a function of the change on the BS to BS distance

We have assumed that the separation of the base stations in the three and two base station case is roughly 10m. This is not fixed. The average separation between the any two base stations however could vary. Generally fiber to the home (FTTH) is used. We now wish to find out the effect of varying this fiber distance on the average delay. As seen in Fig 6.39 the effect is primarily linear. Also the delay for the three base station case is higher than that for the two base station case.

Summary

In this chapter we considered some schemes for alleviating the beam blockage problem by the use of switched beam antennas. We designed a handshake protocol to resolve the beam blocking issue. We then proceeded to design networks that utilize a single base station, two and three base station. Their behavior is compared and contrasted. The sensitivity of these networks to variations in component parameters was also investigated

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

Contributions of this thesis

ROF-based monitoring networks have been considered a promising solution to increase the capacity, coverage, bandwidth, and mobility. One such application that we have envisaged is in highly secure locations which are prone to human attack. In this case high definition video and images could significantly improve the quality of monitoring.

We have considered some of the basic scheduling based algorithms and found them to be unsuitable for our application primarily on account of the fact that they were designed for use at low bit rates. Also they mostly attempt to minimize power consumption. They also are not designed for use in critical applications where failure to detect is not deemed acceptable.

When an emergency occurs, in the protocol we designed, it is possible to obtain data from a single node as the data obtained from other nodes may not be relevant. Adapting schedules according to varying requirements is accomplished using three modes for our MAC protocol. We shall elaborate on this in the next chapter as well. We have also studied the performance of our protocol and considered its dependence on the component timing parameters, number of nodes etc. This was done by performing a Monte Carlo simulation.

At 60GHz the beams are exceedingly narrow and prone to blockage from several factors unlike at lower frequencies. Also since we are considering indoor applications, we have to take into account the fact that people will always be moving around. This further complicates matters as it may lead to beam blockage.

We considered various solutions to alleviate the problem and we decided that the best possible solution involves the use of switched beam antennas. We also concluded that a random selection of beams for transmission is insufficient as a technique for sustaining communication.

We modify our protocol by implementing a handshake exchange before transmission begins. The base station sends out node id and timing as usual but instead of beginning transmission as in the previous case, the node sends out an Acknowledge or ACK signal. Upon receipt of this, the base station shall respond with an ACKREC (Acknowledge Receive). Now if the beam is blocked this process cannot take place.

In the first case we used a single base station, i.e. we do not add any redundancy. This greatly simplifies design and reduces cost but as we shall see, guaranteed end to end communication may not always be guaranteed. Now if the beam is detected as blocked we proceed as indicated in the sate machine diagram below. If the base station does not receive the ACK signal, then it knows that it has to switch by one beam. Since the base station has not received the ACK signal it shall not transmit the ACKREC signal, hence the node knows that the beam is blocked then it too shall shift the beam by 1. We now send the id and timing using the second set of beams, if the process takes place as desired then it is acceptable, otherwise we shall repeat the process till we get a set of beams through which communication can proceed.

We also proposed a scheme in which three base stations were used. In this case, the node then exchanges the handshake with the secondary base station # 1 and then uses this to determine signal strength. The node then exchanges the handshake with the secondary base station # 2 and then uses this to determine signal strength. It then compares the two and uses it to decide which one to communicate with.

In the third scheme that we proposed, we used two base stations and in case one beam was blocked, the other was used to communicate with the beam. In this way end to end communication was guaranteed. We also described a scheme that enables us to determine the position of the second Base Station.

Future Work

The function of the MAC protocol can be broadly divided into three categories [17]:

iv. Channel Access Policies

v. Scheduling and Buffer Management

vi. Error Control

We have in this work primarily focused on the first aspect of this work. In the future, parts ii and iii will have to be dealt with as the deal with the issues of flow control and error control. This would be a significant extension in the scope of this research.

Another extension that is necessary is the description of the protocol to enable information transfer between the base station and the central controller. This information transfer takes place through the fiber network. This is the next stage of the process of development of the protocol. It must be noted just as there are several nodes per base station, there are also several base stations per central controller. Hence, it is important to implement this stage.

Most importantly, it is important to develop the hardware that enables this transmission to take place. The development of fully integrated chips that accomplish this is of primary importance. The architecture of the base station and the node are described in chapter 3. This will then enable us to implement the networks and then study their behavior.

APPENDIX A

NEWTON'S METHOD

The following is a discussion on the mathematical background needed to utilize Newton's method as described in chapter 6. It has been adapted from [29,30]

Iterative Methods for Optimization

The constrained optimization problem is to minimize a function f over a set $U \subset R^N$.

<u>Definition</u>

A local minimizer, therefore, is an $x *\in U$such that *f (x *)* ≤ *f (x)* for all $x \in U$ near x

It is standard to express this problem as $min_{x\in U} f(x)$

<u>Definition</u>

A global minimizer is a point $x *\in U$ such that *f (x *)* ≤ *f (x)* for all $x \in U$

Sufficient Condition

<u>Theorem</u>

Let f be twice continuously differentiable in a neighborhood of x. Assume that $\nabla f(x) = 0$ and that $\nabla^2 f(x)$ is positive definite. Then x is a local minimizer of f.

We shall define a series of x's, starting from an initial guess x0, s.t. the series converges towards x * which satisfies f'(x *) = 0. This x * will also be an extremum, i.e. stationary point, of f

The second order Taylor expansion of f(x),

$$f(x + \Delta x) = f(x) + f'(x)\Delta x + \frac{1}{2} f''(x)\Delta x^2,$$

attains its extremum when Δx solves the linear equation:

$$f'(x) + f''(x)\Delta x = 0.$$

Alternatively, one may expand f'(x) to first order in Δx,

$$f'(x + \Delta x) = f'(x) + \Delta x f''(x)$$

giving us the same equation as above when we require f ' = 0. Thus, provided that $f(x)$ is a twice-differentiable function and the initial guess x_0 is chosen close enough to x_* , the sequence (x_n) defined by

$$x_{n+1} = x_n - \frac{f'(x_n)}{f''(x_n)},\ n \geq 0$$

will converge towards the root of f', i.e. x_* for which $f'(x_*) = 0$.

The geometric interpretation of Newton's method is that at each iteration one approximates $f(\mathbf{x})$ by a quadratic function around $\mathbf{x}_n$, and then takes a step towards the maximum/minimum of that quadratic function. (If f(x) happens to be a quadratic function, then the exact extremum is found in one step.)

The above iterative scheme can be generalized to several dimensions by replacing the derivative with the gradient, $\nabla f(\mathbf{x})$, and the reciprocal of the second derivative with the inverse of the Hessian matrix, $Hf(\mathbf{x})$. One obtains the iterative scheme

$$\mathbf{x}_{n+1} = \mathbf{x}_n - [Hf(\mathbf{x}_n)]^{-1}\nabla f(\mathbf{x}_n),\ n \geq 0.$$

Usually Newton's method is modified to include a small step size $\gamma > 0$

$$\mathbf{x}_{n+1} = \mathbf{x}_n - \gamma[Hf(\mathbf{x}_n)]^{-1}\nabla f(\mathbf{x}_n).$$

This is often done to ensure that the Wolfe conditions are satisfied at each step $\mathbf{x}_n \to \mathbf{x}_{n+1}$ of the iteration.

Newton's method converges much faster towards a local maximum or minimum than gradient descent. In fact, every local minimum has a neighborhood N such that, if we start with $\mathbf{x}_0 \in N$, Newton's method with step size γ = 1 converges quadratically (if the Hessian is invertible in that neighborhood).Finding the inverse of the Hessian is an expensive operation, so the linear equation

$$\mathbf{p}_n = \mathbf{x}_{n+1} - \mathbf{x}_n = -[Hf(\mathbf{x}_n)]^{-1}\nabla f(\mathbf{x}_n), \ n \geq 0..$$

is often solved approximately (but to great accuracy) using a method such as conjugate gradient. There also exist various quasi-Newton methods, where an approximation for the Hessian is used instead.

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VITA

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